Reactor Neutrino Experiments

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INFO 05
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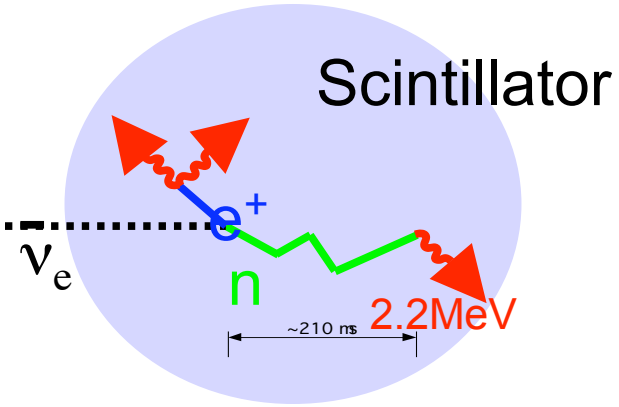
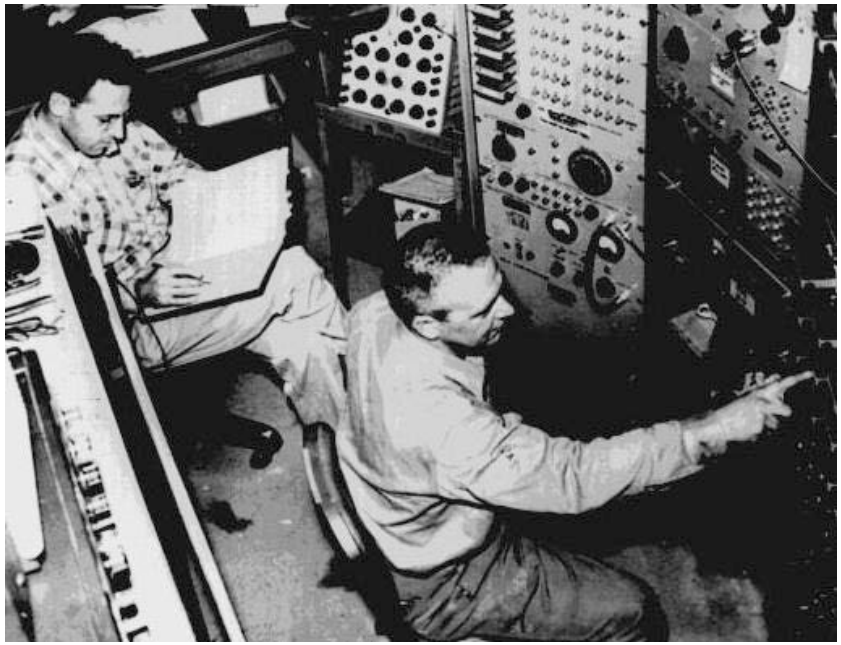
First Direct Detection of the Neutrino



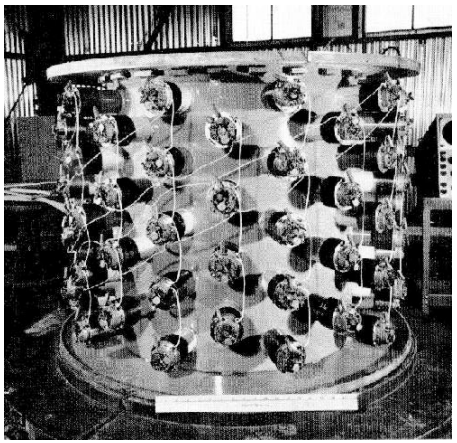
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\tau \approx 200\ \mu s$$

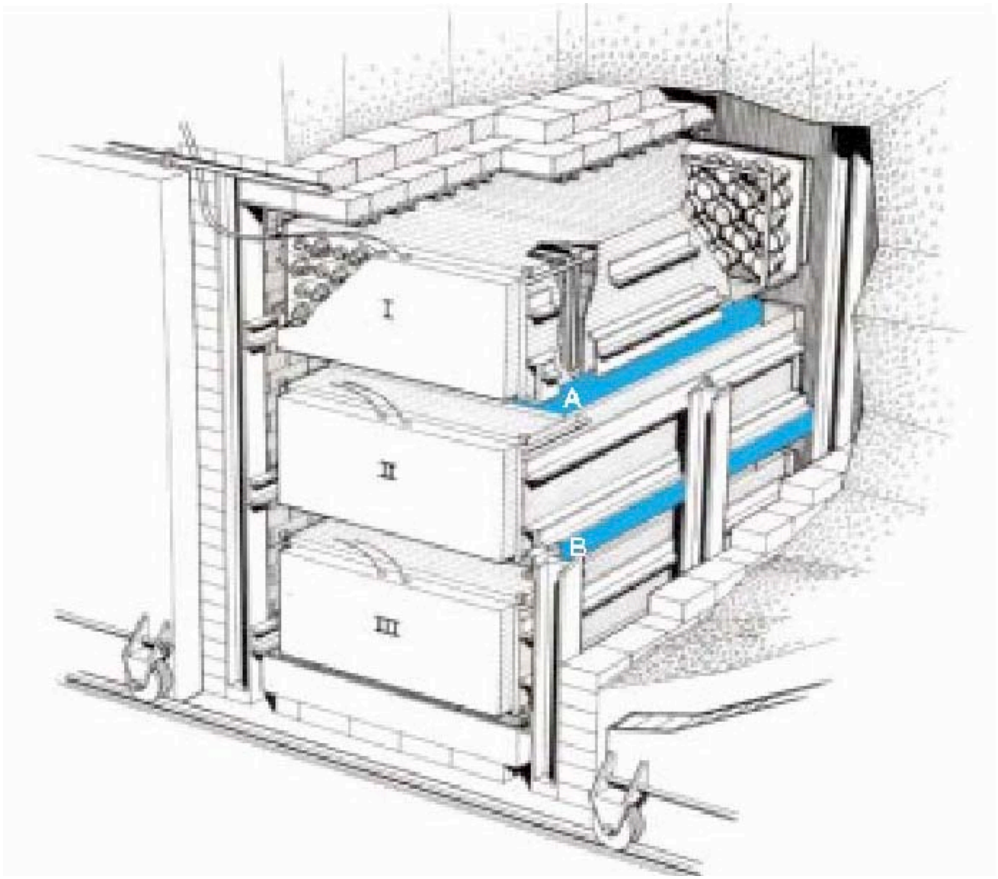
$$n + p \rightarrow d + \gamma\,(2.2\ MeV)$$



$$E_{prompt} \cong E_\nu - \overline{E_n} - 0.8\ MeV$$



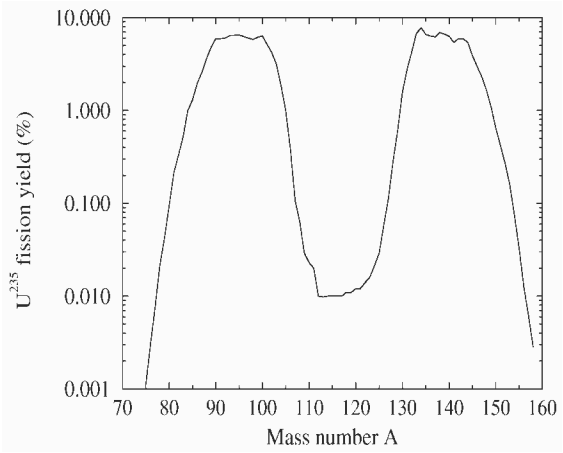
Reines and Cowan 1956

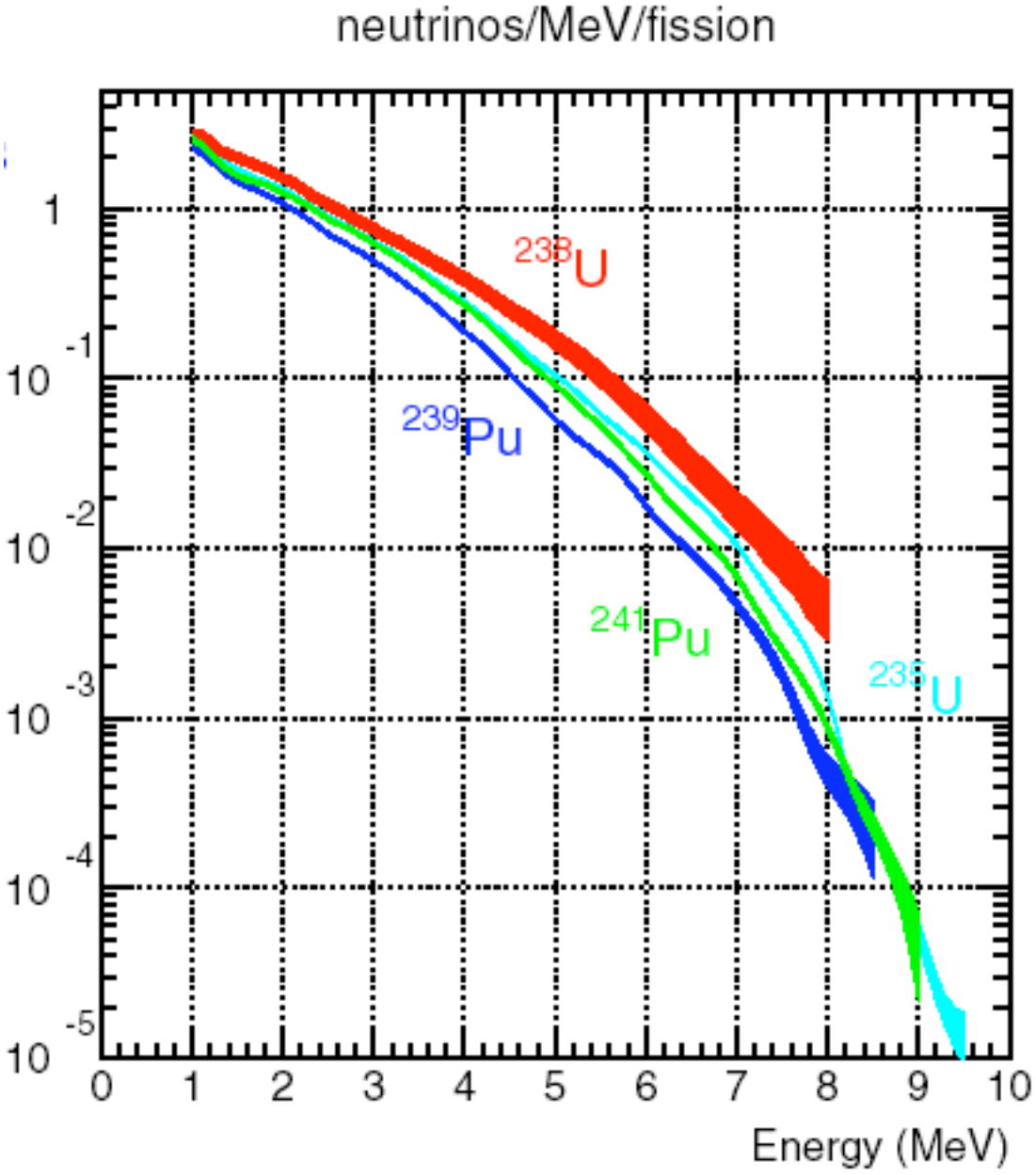


The version of Reines' experiment that worked

Neutrino Spectra from Principal Reactor Isotopes

^{235}U fission



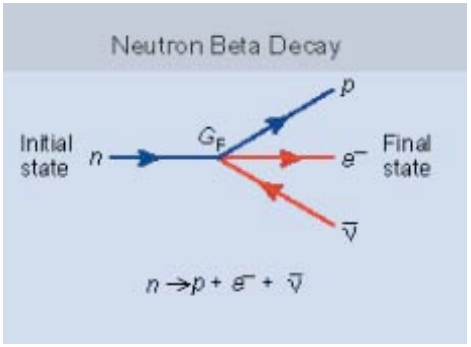


~200 MeV per fission

~6 $\bar{\nu}_e$ per fission

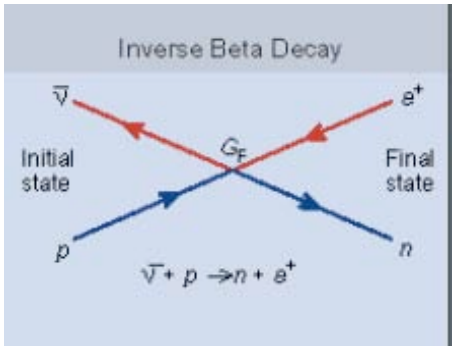
~2 x 10^{20} $\bar{\nu}_e$/GW_{th}-sec

Inverse Beta Decay Cross Section



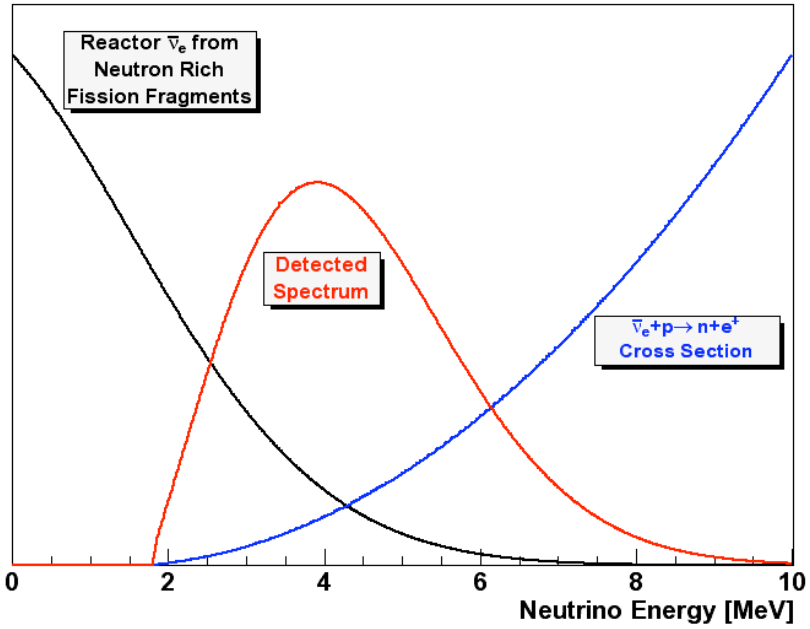
$$\sigma_{\text{tot}}^{(0)} = \sigma_0 (f^2 + 3g^2) E_e^{(0)} p_e^{(0)}$$

$$= 0.0952 \left(\frac{E_e^{(0)} p_e^{(0)}}{1\ \text{MeV}^2} \right) \times 10^{-42}\ \text{cm}^2$$

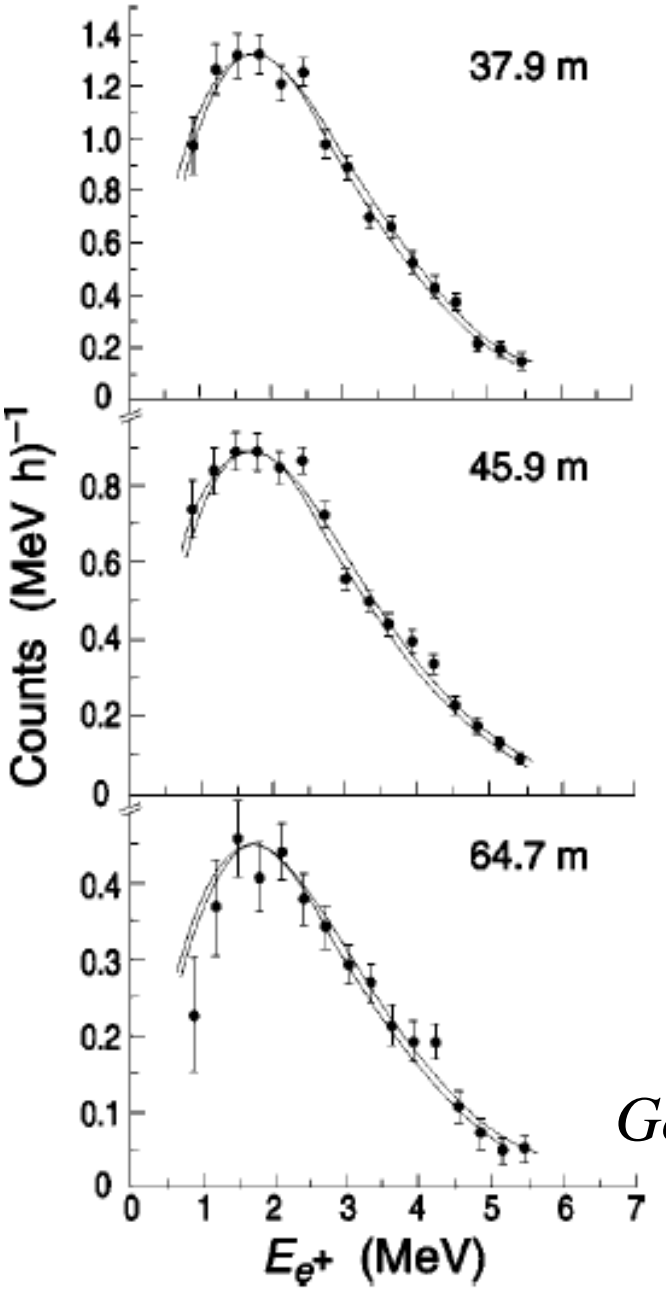


$$\sigma_0 = \frac{G_F^2 \cos^2 \theta_C}{\pi} (1 + \Delta_{inner}^R) \qquad \sigma_{\text{tot}}^{(0)} = \frac{2\pi^2 / m_e^5}{f_{p.s.}^R \tau_n} E_e^{(0)} p_e^{(0)}$$

Neutrino Spectrum



Positron Spectrum



Goesgen

Neutrino mixing matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

SuperK, K2K

$\theta_{23} = \sim 45°$

?

Reactors
Accelerators

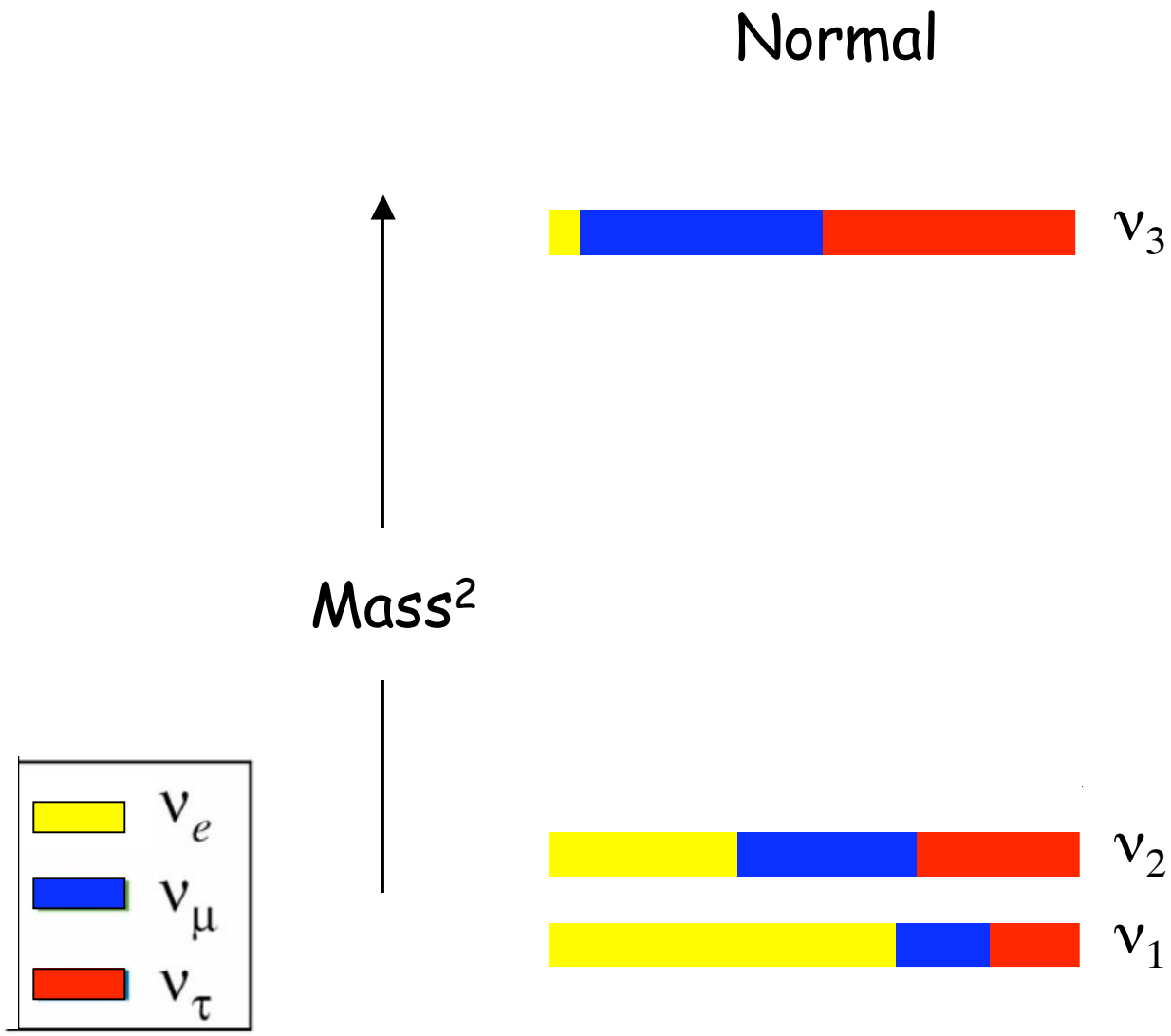
SNO, SuperK, KamLAND

$\theta_{12} \sim 32°$

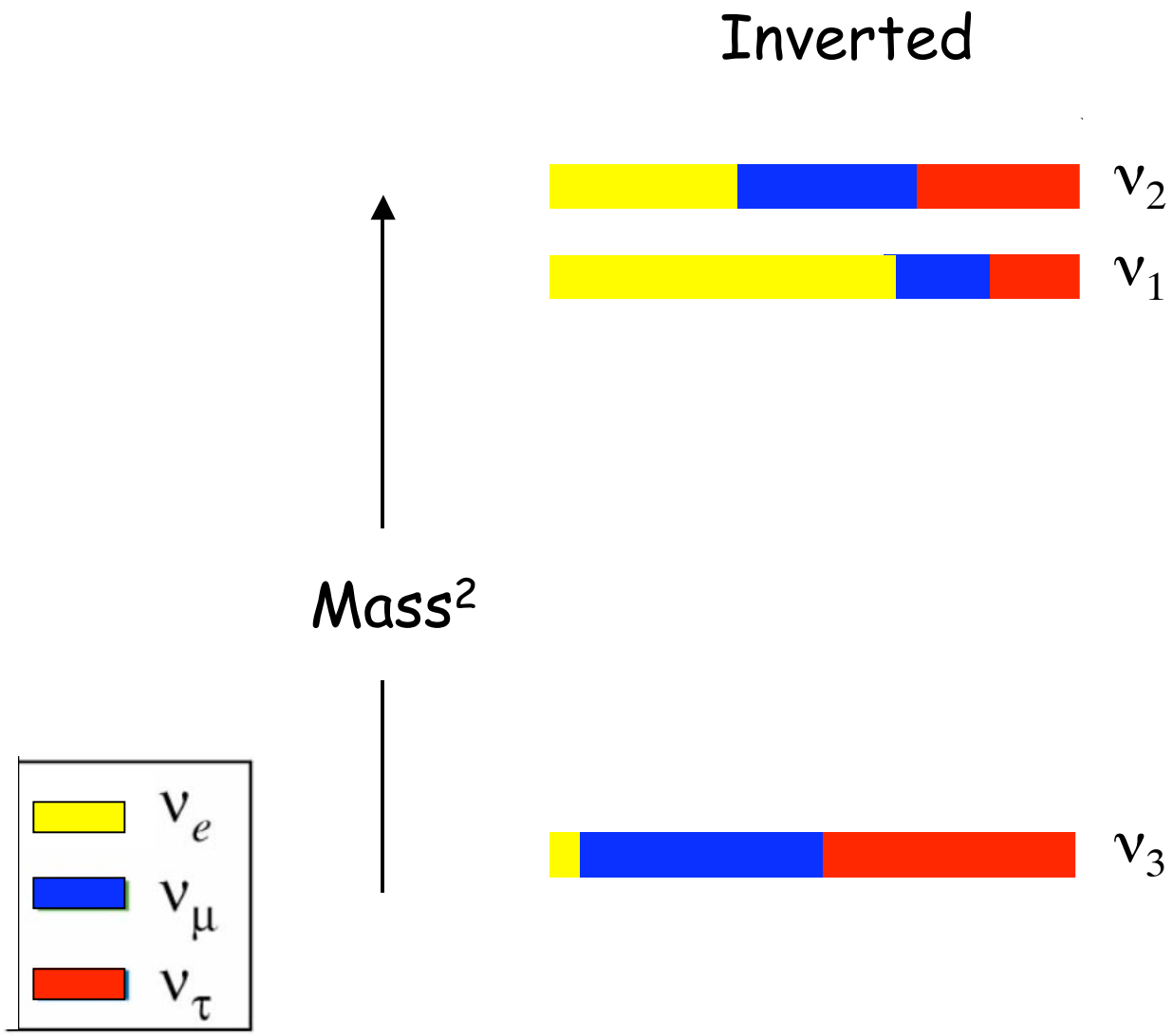
?

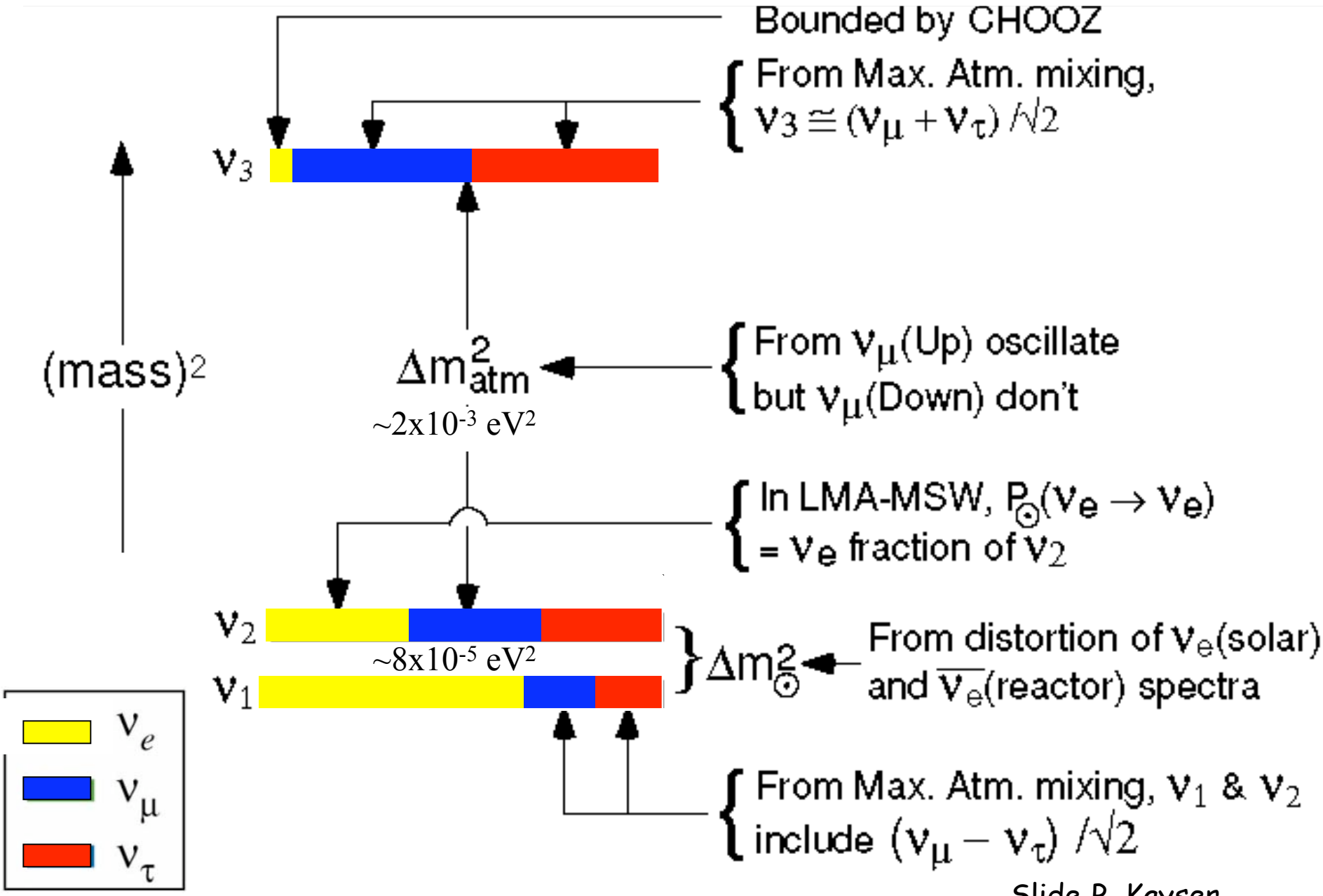
$0\nu\beta\beta$

Neutrino Mass



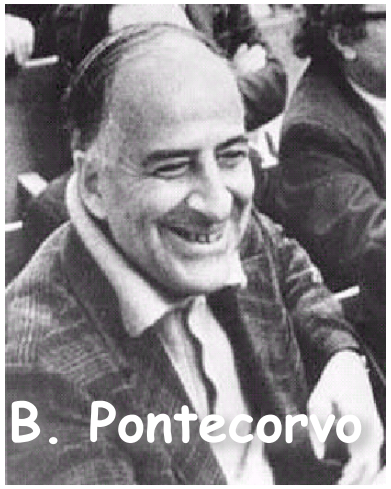
Neutrino Mass

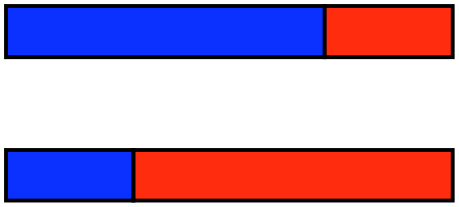




Slide B. Kayser

Neutrino Oscillations





$E_2 = m_2 c^2$

$E_1 = m_1 c^2$

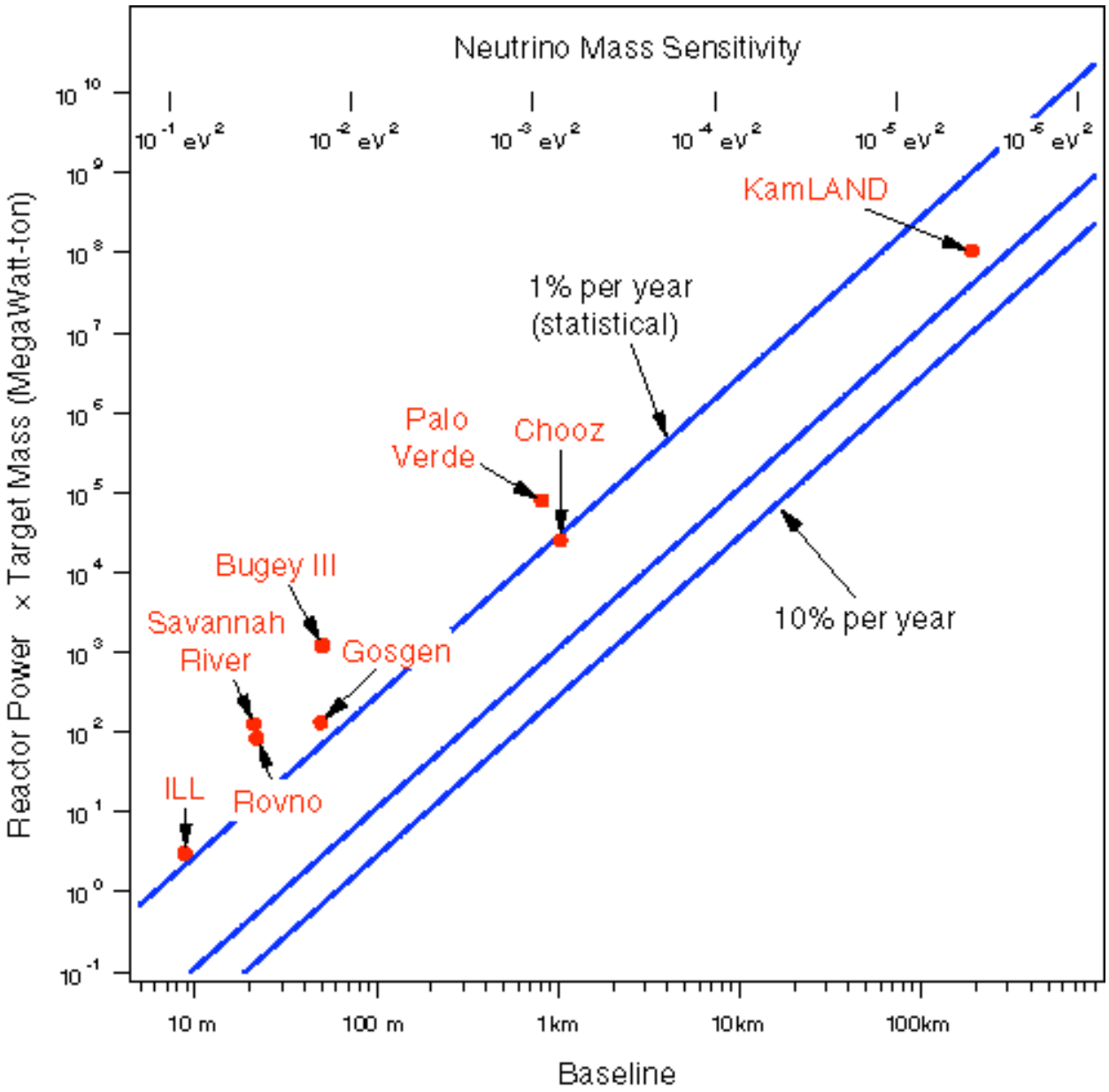
In the rest frame

$$\left|\Psi_e(t)\right\rangle = \cos(\theta) e^{-im_1 c^2 t/\hbar} \left|\nu_1\right\rangle + \sin(\theta) e^{-im_2 c^2 t/\hbar} \left|\nu_2\right\rangle$$

$$\left|\left\langle \Psi_e(t) \middle| \Psi_e(0) \right\rangle\right|^2 = 1 - \sin^2(2\theta) \sin^2\left(\frac{(m_2 - m_1)c^2}{2\hbar} t\right)$$

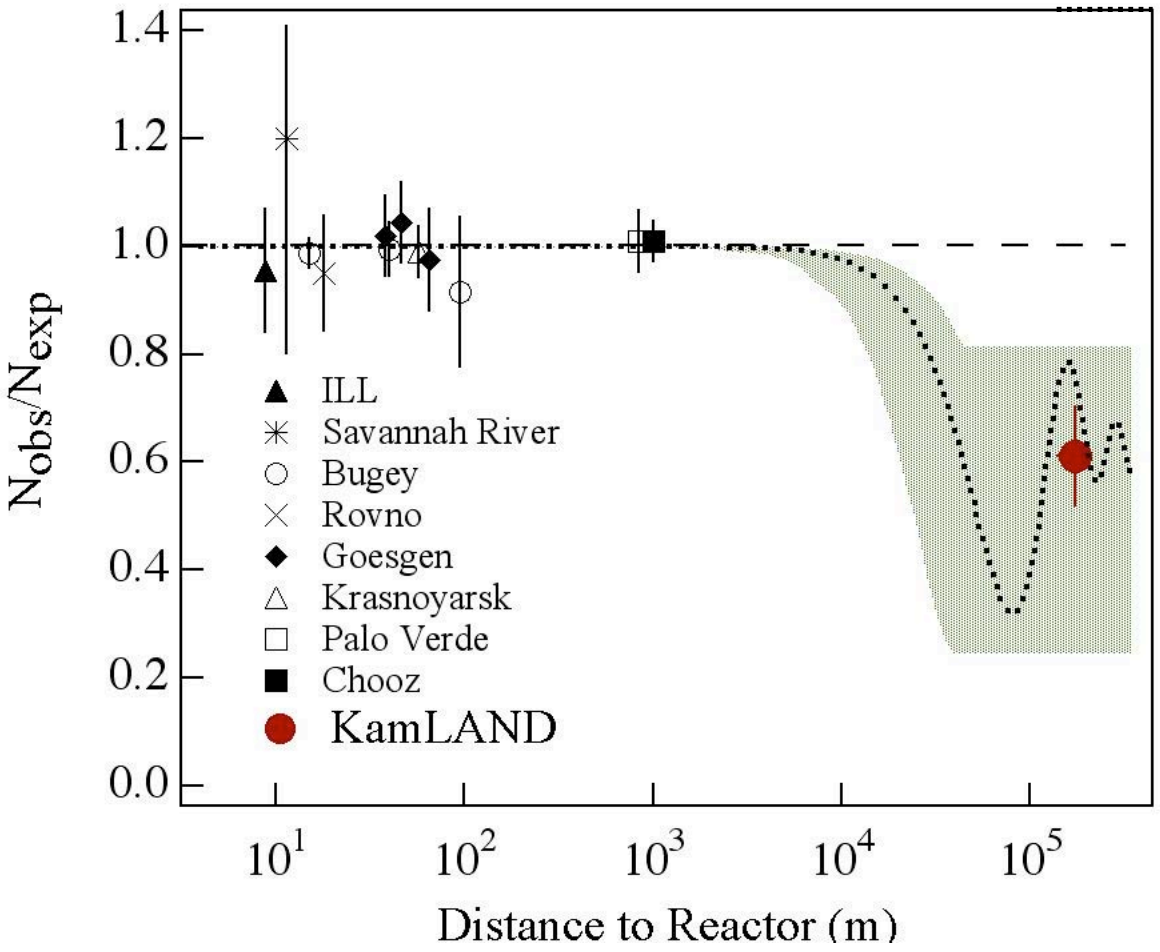
Boost to the lab frame

$$P_{ee} = 1 - \sin^2(2\theta) \sin^2\left(1.27 \frac{\Delta m_{12}^2 L}{E}\right)$$

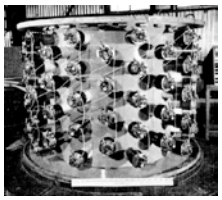


Long-Baseline Reactor-Anti-Neutrino Experiments

Reactor Disappearance



Monolithic Anti-Neutrino Detectors

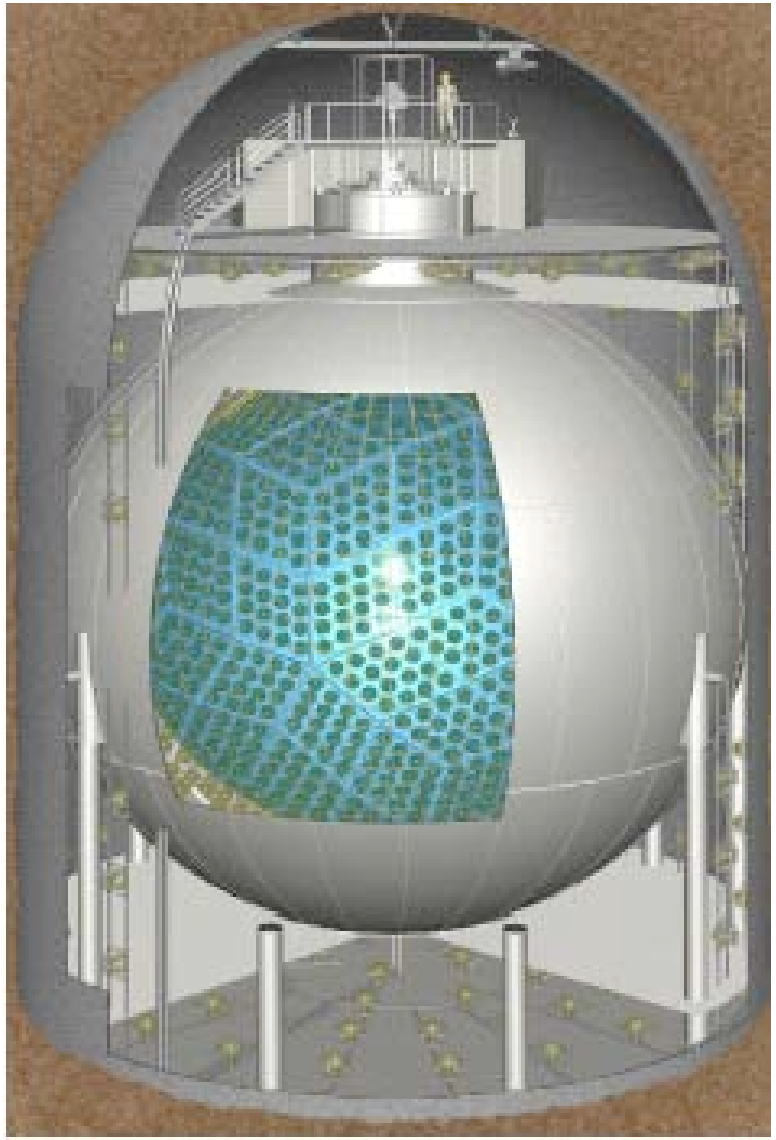


1m

Poltergeist

4 m

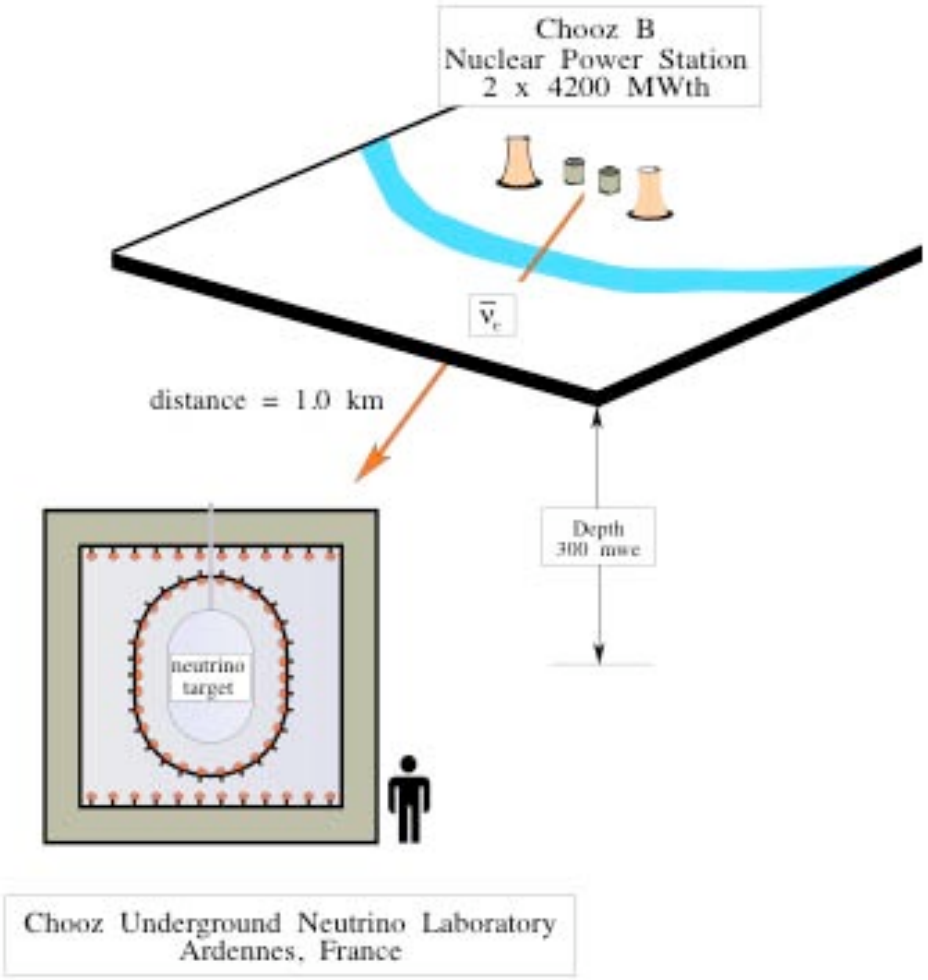
CHOOZ



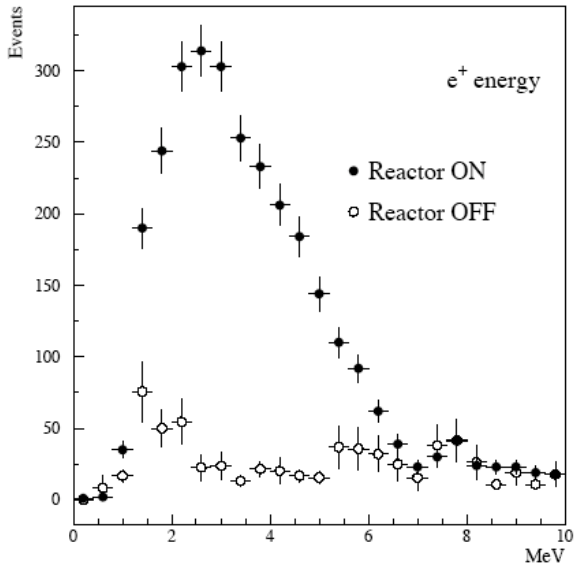
20 m

KamLAND

CHOOZ

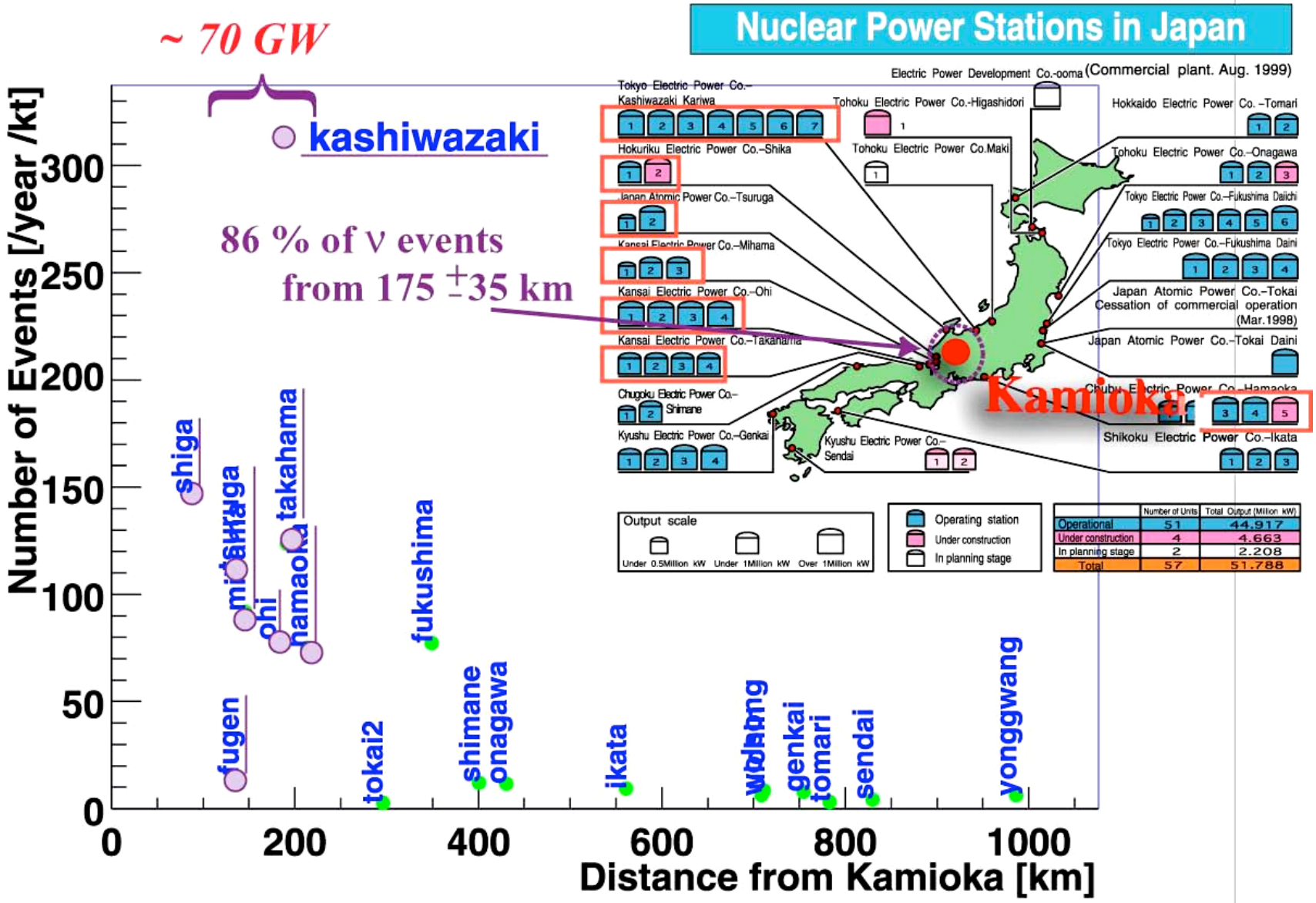


Chooz Underground Neutrino Laboratory
Ardennes, France

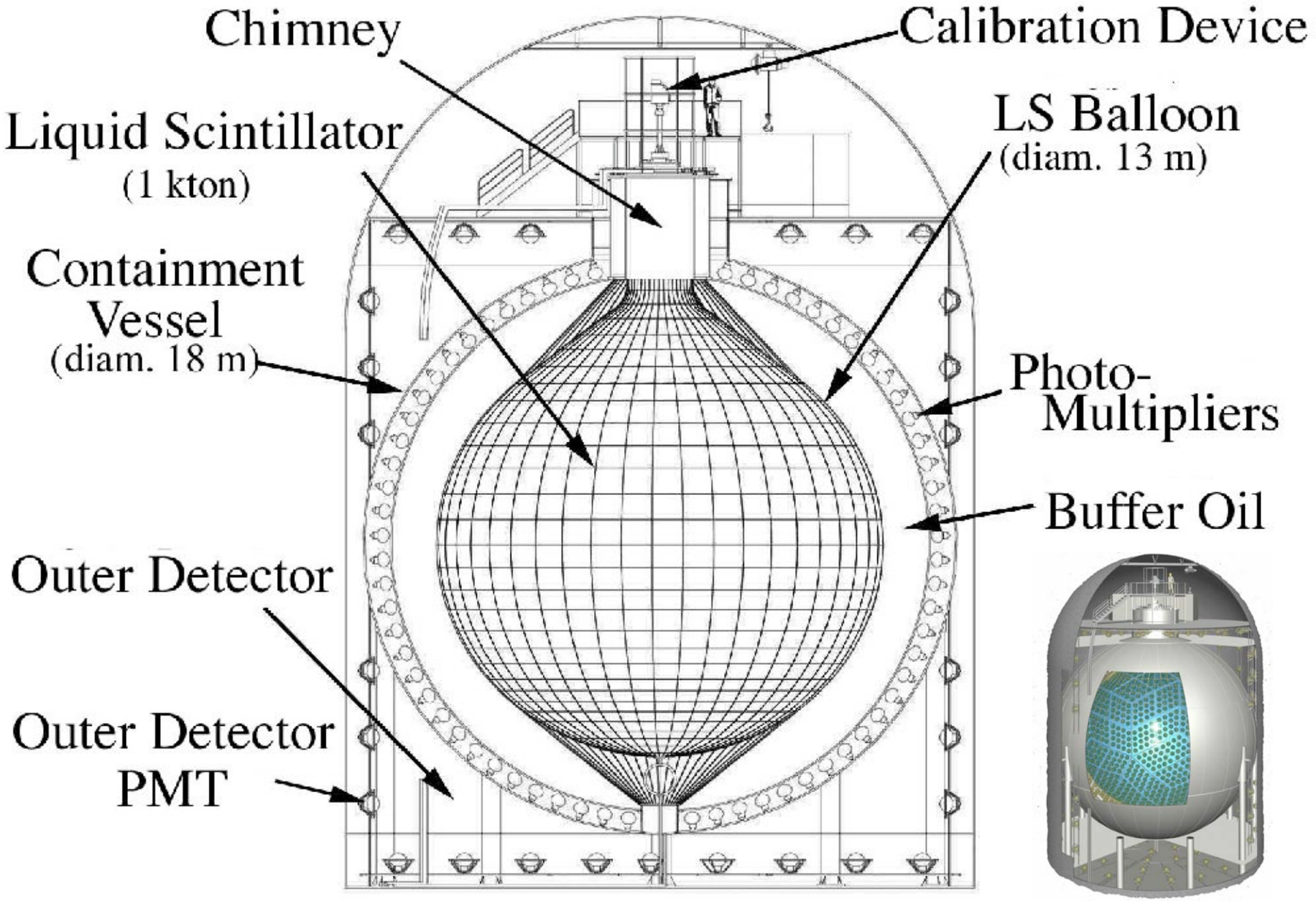


20 % of world nuclear power

~ 70 GW

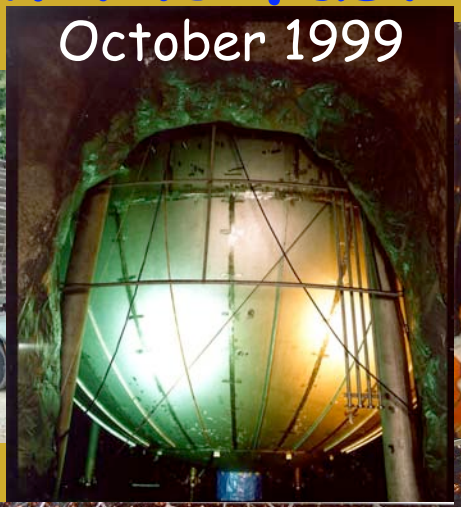


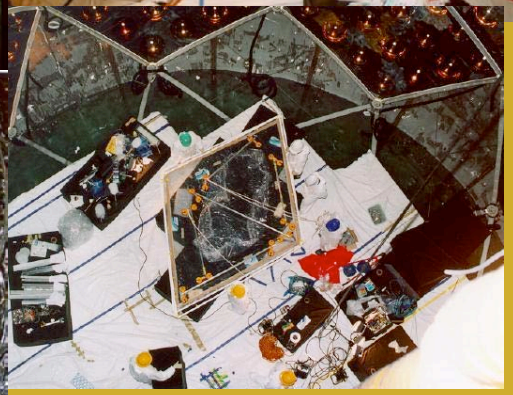
KamLAND Underground Laboratory

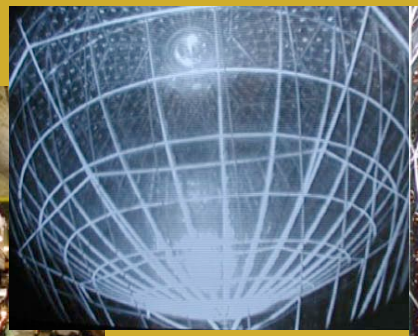


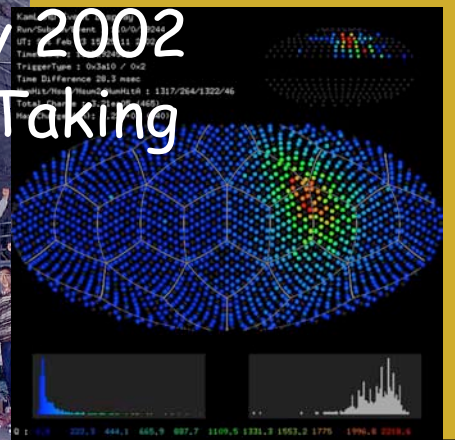
3.2 ton water veto

KamLAND on the fast track

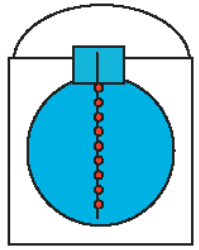


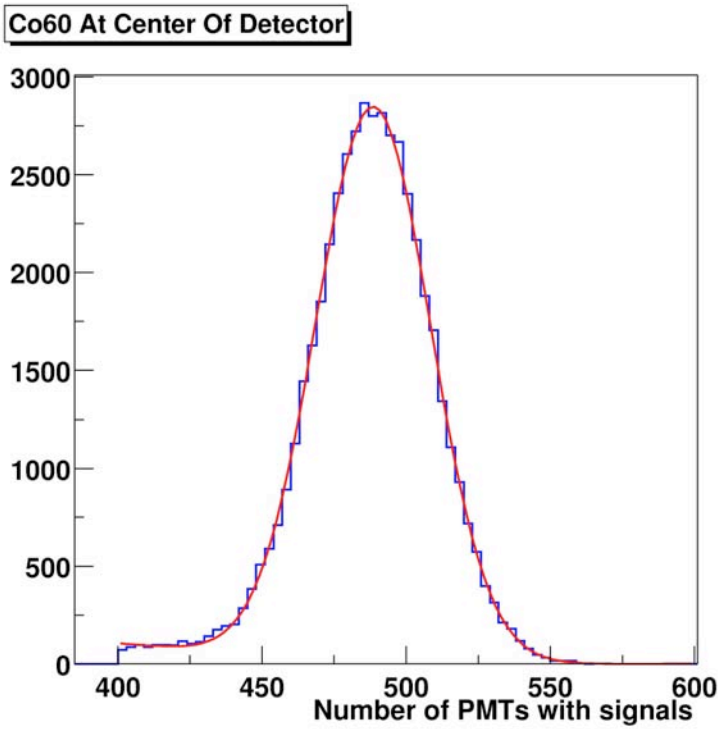


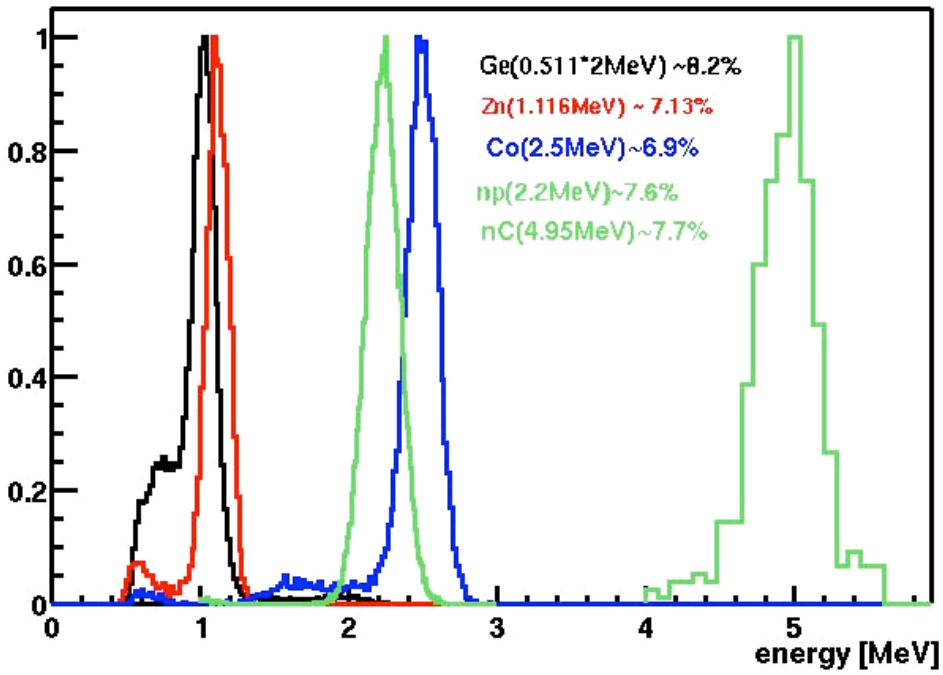




Detector Energy Scale and Response







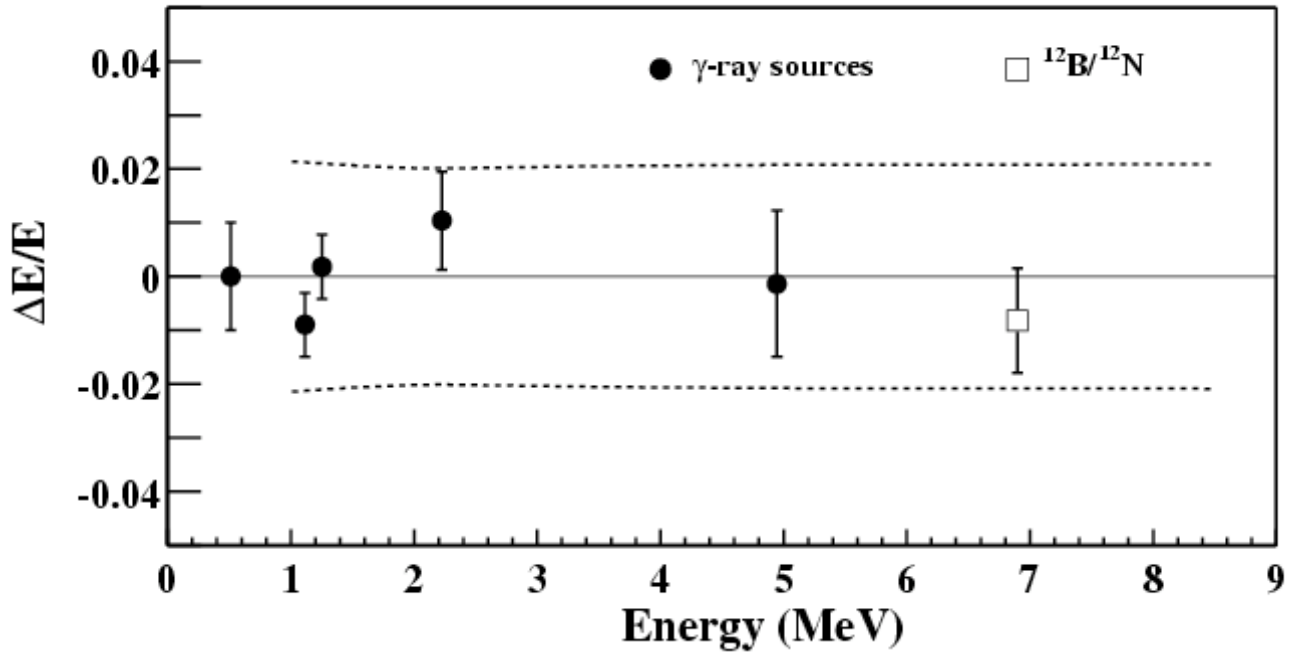
^{60}**Co**: 1.173+1.333 MeV

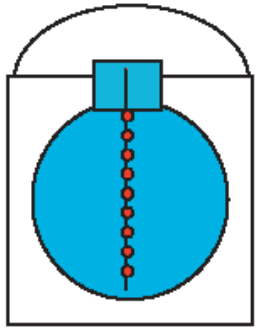
$\Delta E/E \sim 7.5\% / \sqrt{E}$ 17" tubes alone

$\Delta E/E \sim 6.2\% / \sqrt{E}$ 17" and 20"

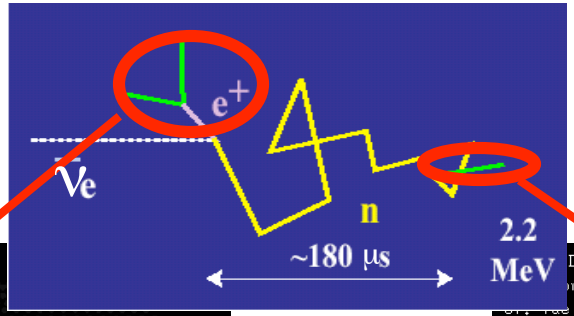
.

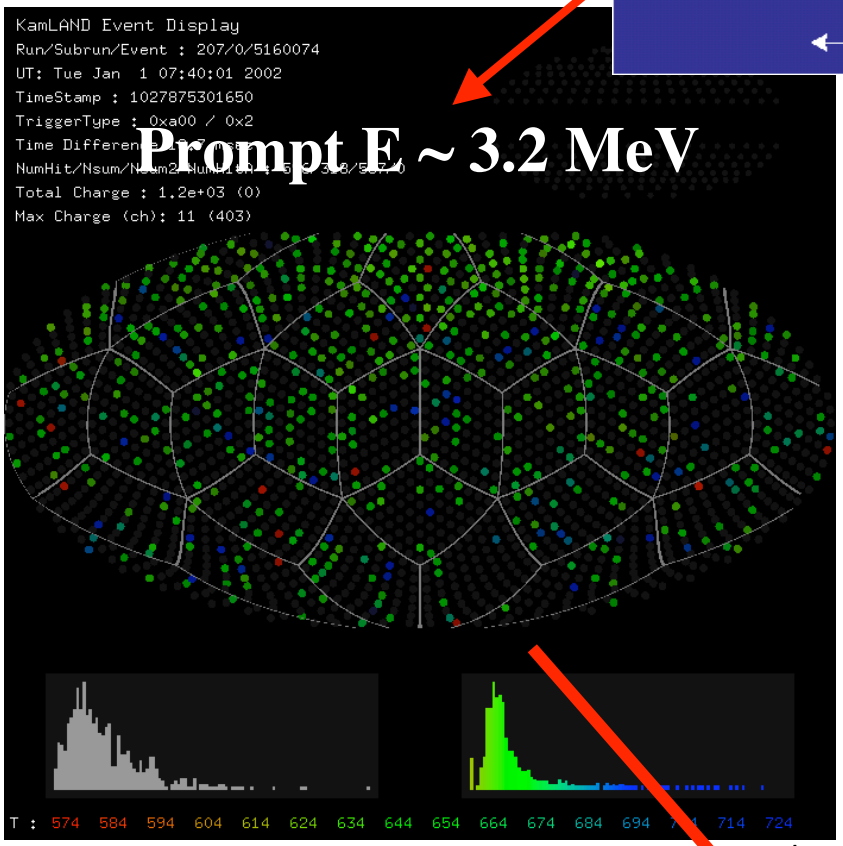
Uniformity of detector response



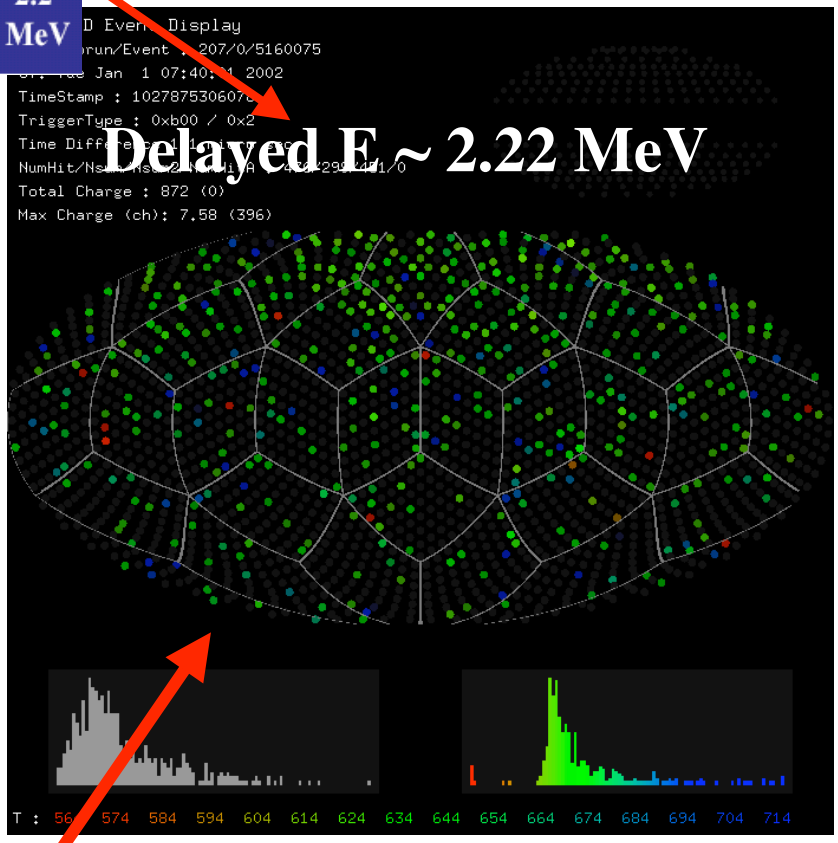


$\Delta E/E \sim 6.2\% / \sqrt{E}$





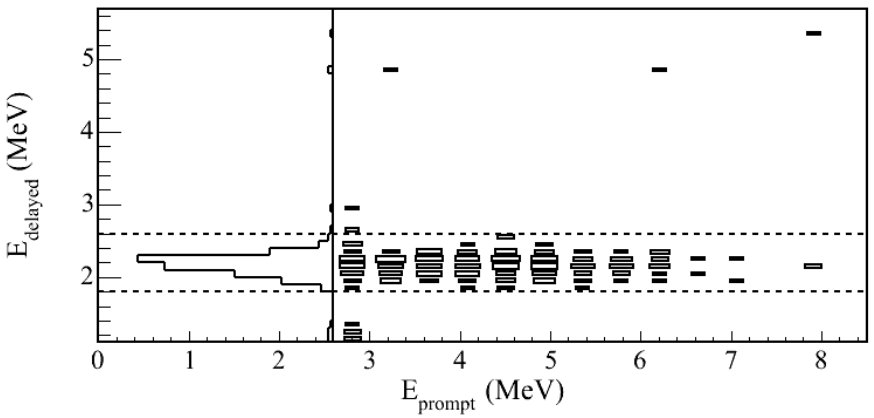
Prompt E ~ 3.2 MeV

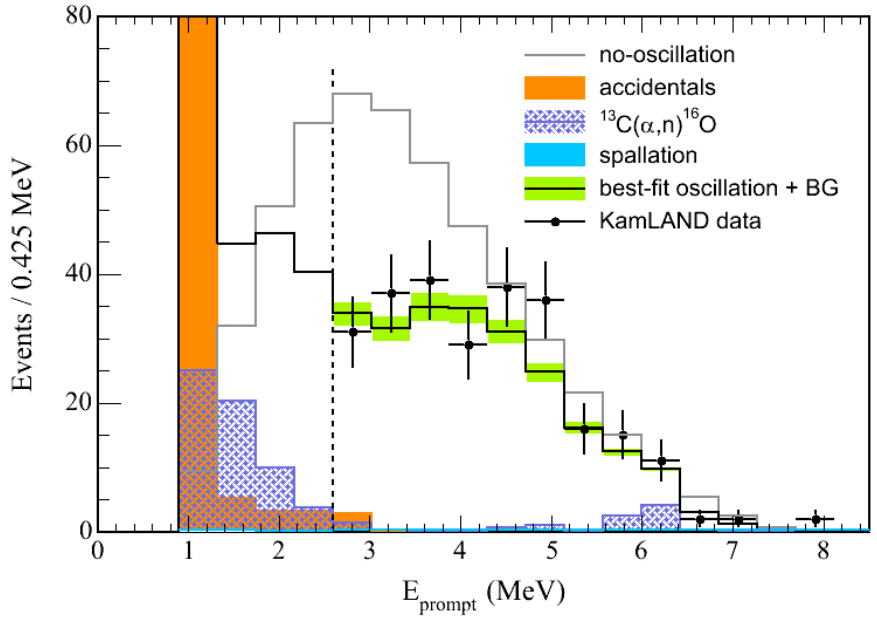


Delayed E ~ 2.22 MeV

Δt~110 μsec
ΔR~0.35 m

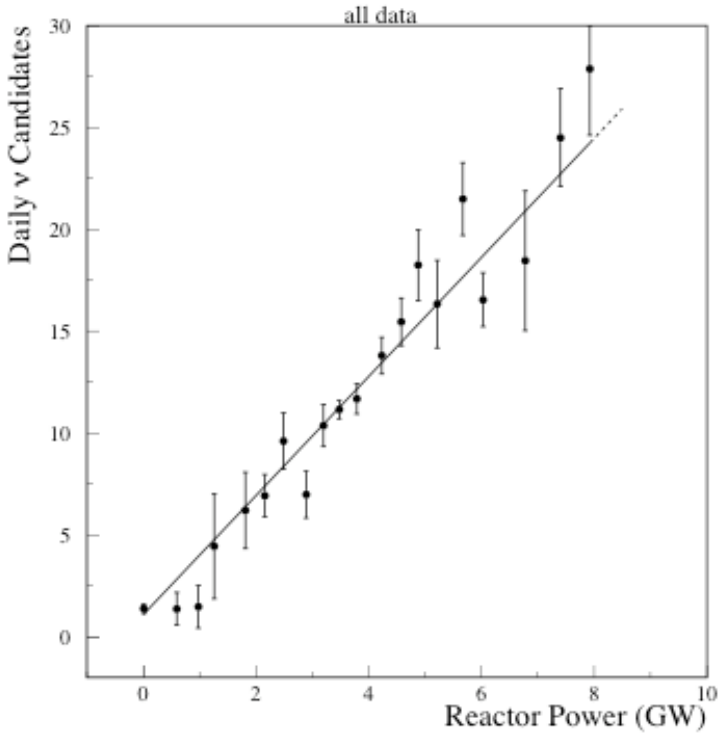
Candidate Neutrino Event



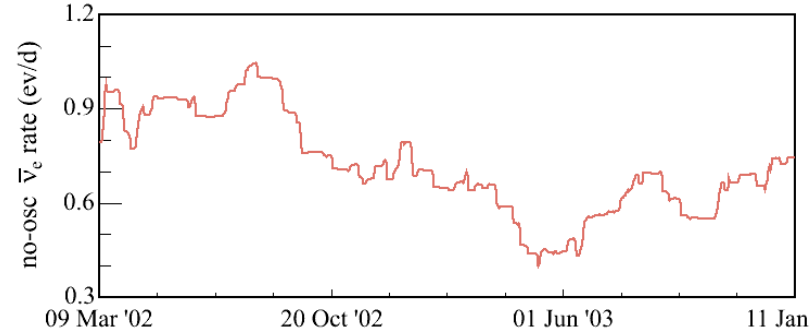


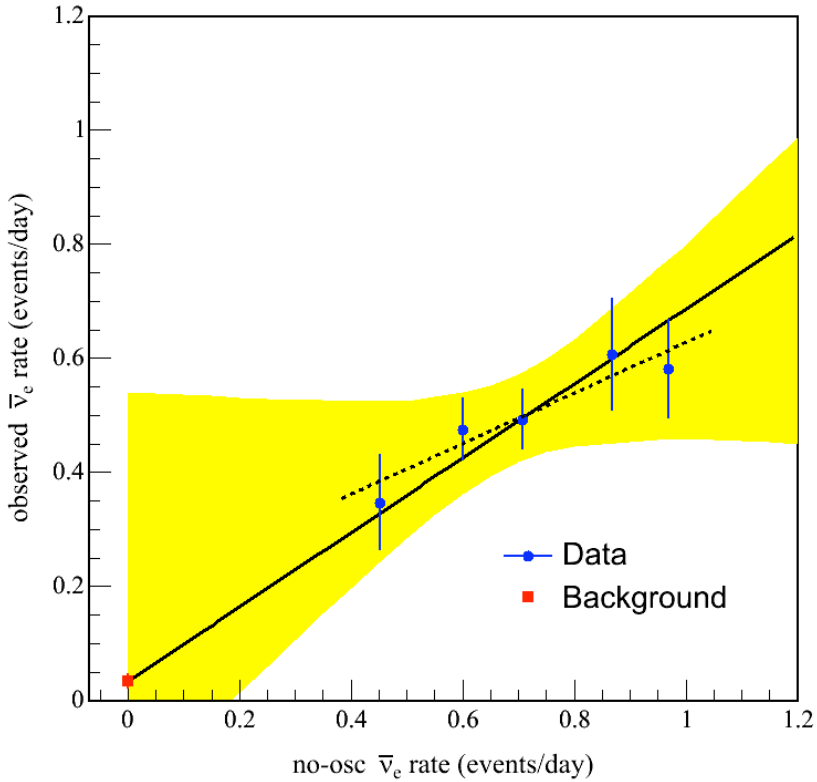
χ^2 / 11 d.o.f = 13

Chooz Correlation of Count Rate and Reactor Power



KamLAND Correlation of Count Rate and Reactor Power





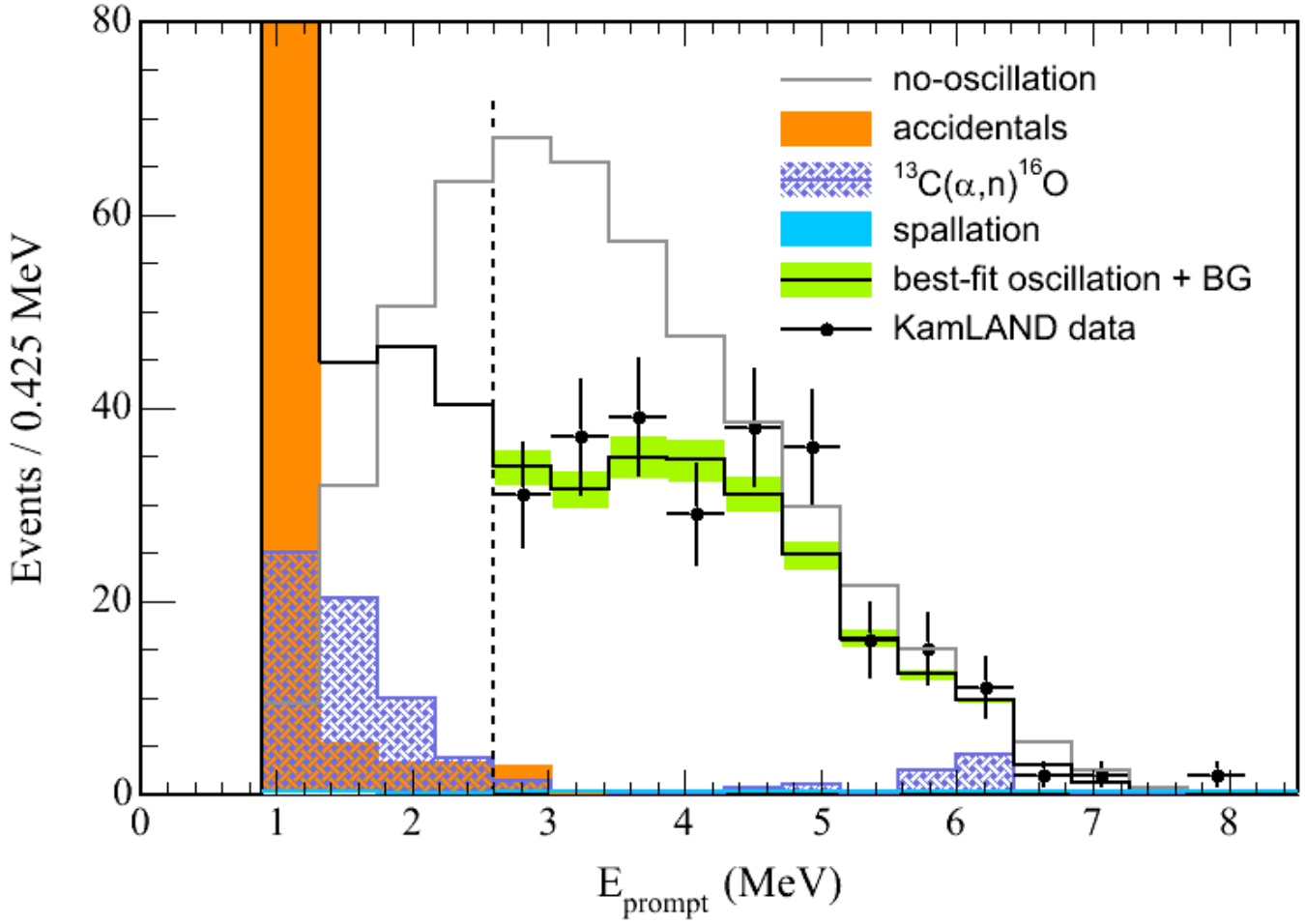
Systematic Uncertainties

E > 2.6 MeV

	%
Fiducial mass ratio	4.7
Energy threshold	2.3
Efficiency of cuts	1.6
Live time	0.06
Reactor power	2.1
Fuel composition	1.0
$\bar{\nu}_e$ cross section	0.2
Total uncertainty	6.5 %

2004 Data Set

Is the Neutrino Spectrum Distorted?

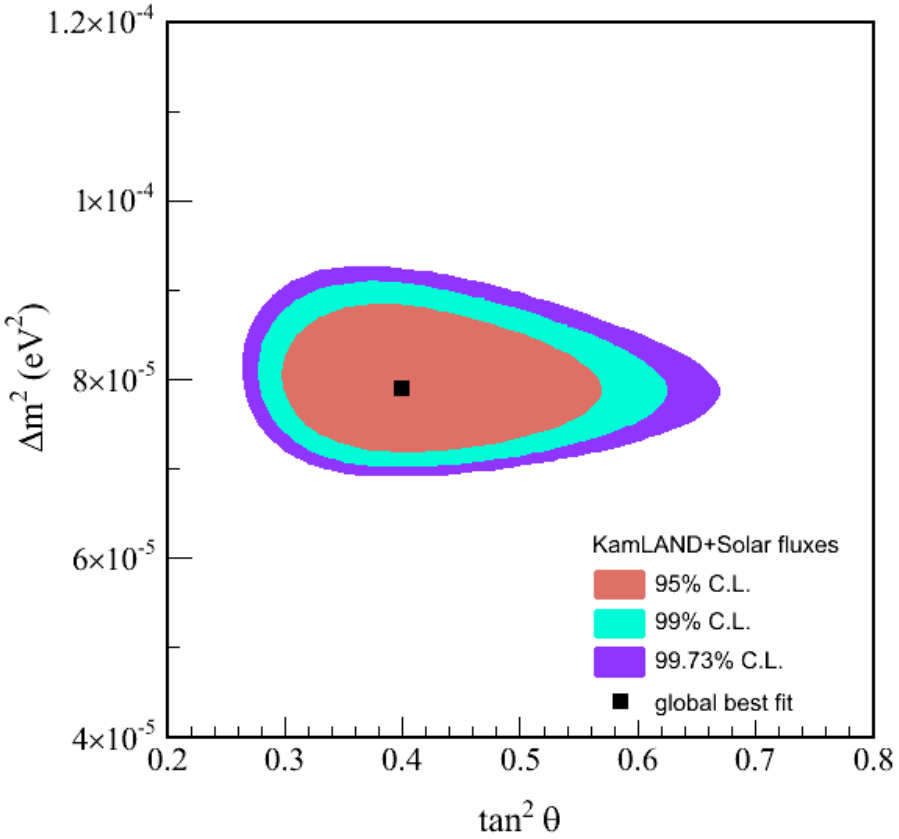


11.1% χ^2_p/DOF = 24.2/17.

0.4% (χ^2_p/DOF = 37.3/18).

χ^2 / 11 d.o.f = 13

Global Fit to KamLAND and Solar Experiments

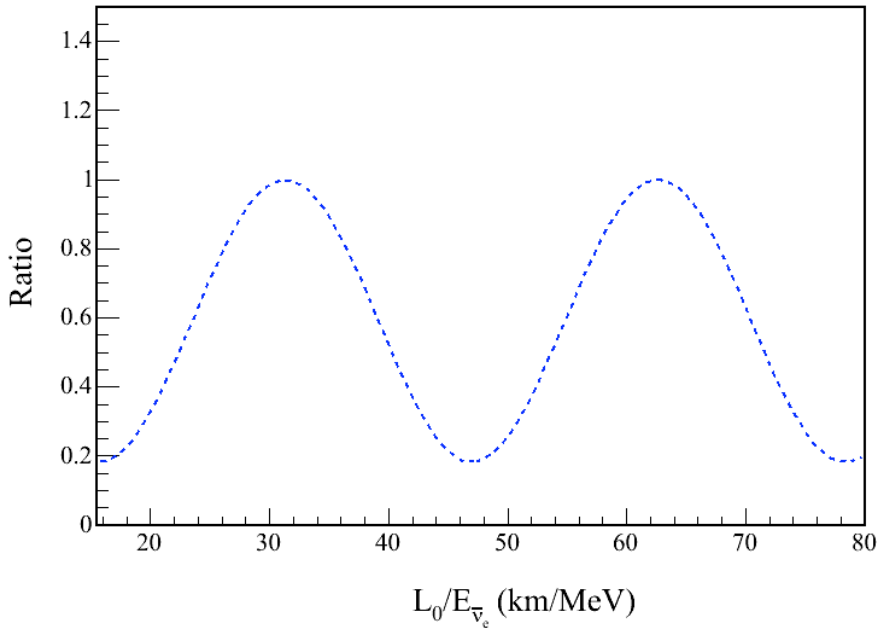


Looking for the oscillation effect

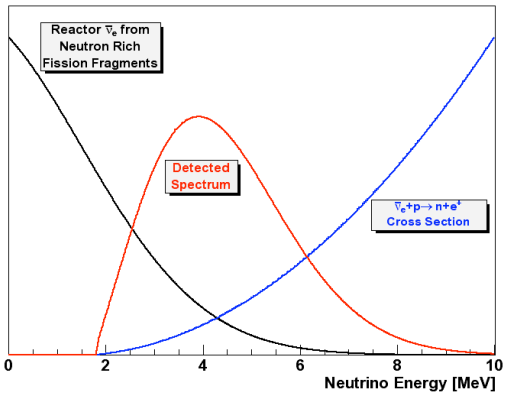
$$\left|\langle \Psi_e(t) | \Psi_e(0) \rangle\right|^2 = 1 - \sin^2(2\theta)\sin^2\left(\frac{(m_2 - m_1)c^2}{2\hbar} t\right)$$

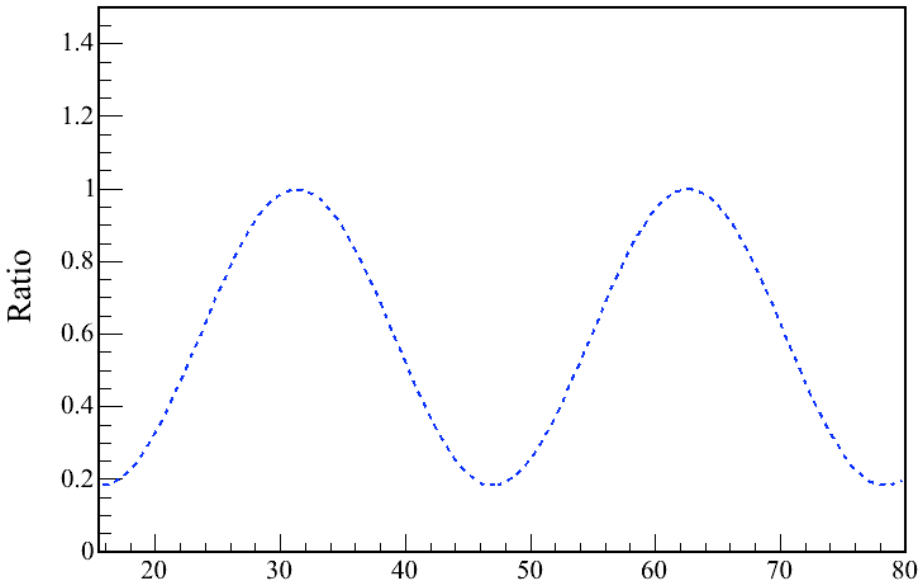
$$P_{ee} = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{(m_2^2 - m_1^2)L}{E}\right)$$

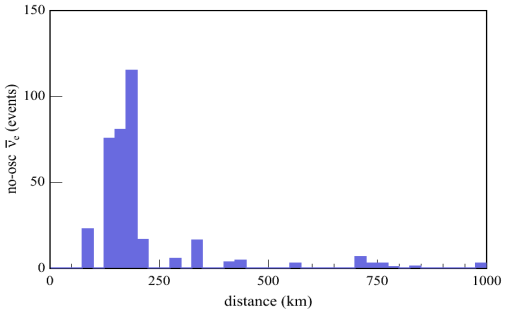
$$L = c \bullet t_{lab} \qquad t_{restframe} = \frac{t_{lab}}{\gamma} = \frac{m}{E} t_{lab}$$

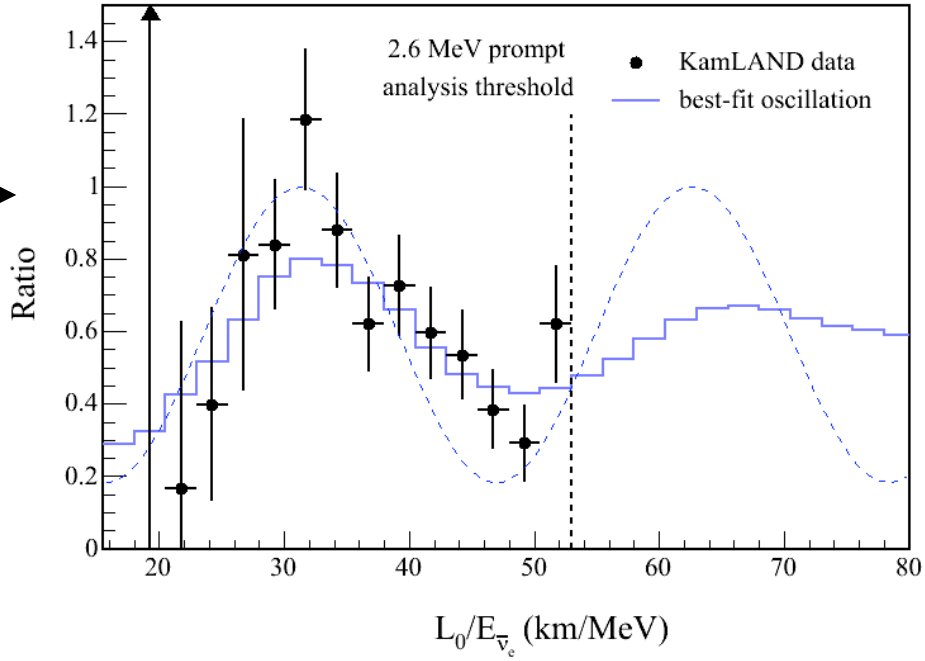


Observing the oscillations in the neutrino rest frame

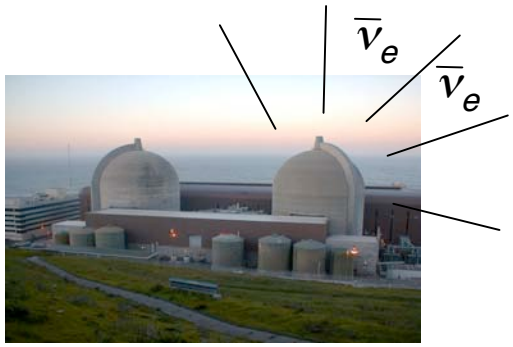








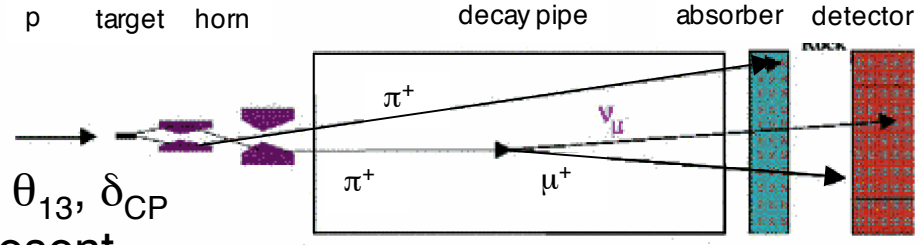
•An expeditiously deployed multidetector reactor experiment with sensitivity to ν_e disappearance down to $\sin^2 2\theta_{13} = 0.01$, an order of magnitude below present limits.



- disappearance experiment $\bar{\nu}_e \rightarrow \bar{\nu}_e$
- look for rate deviations from $1/L^2$ and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline *O(1 km),* no matter effects

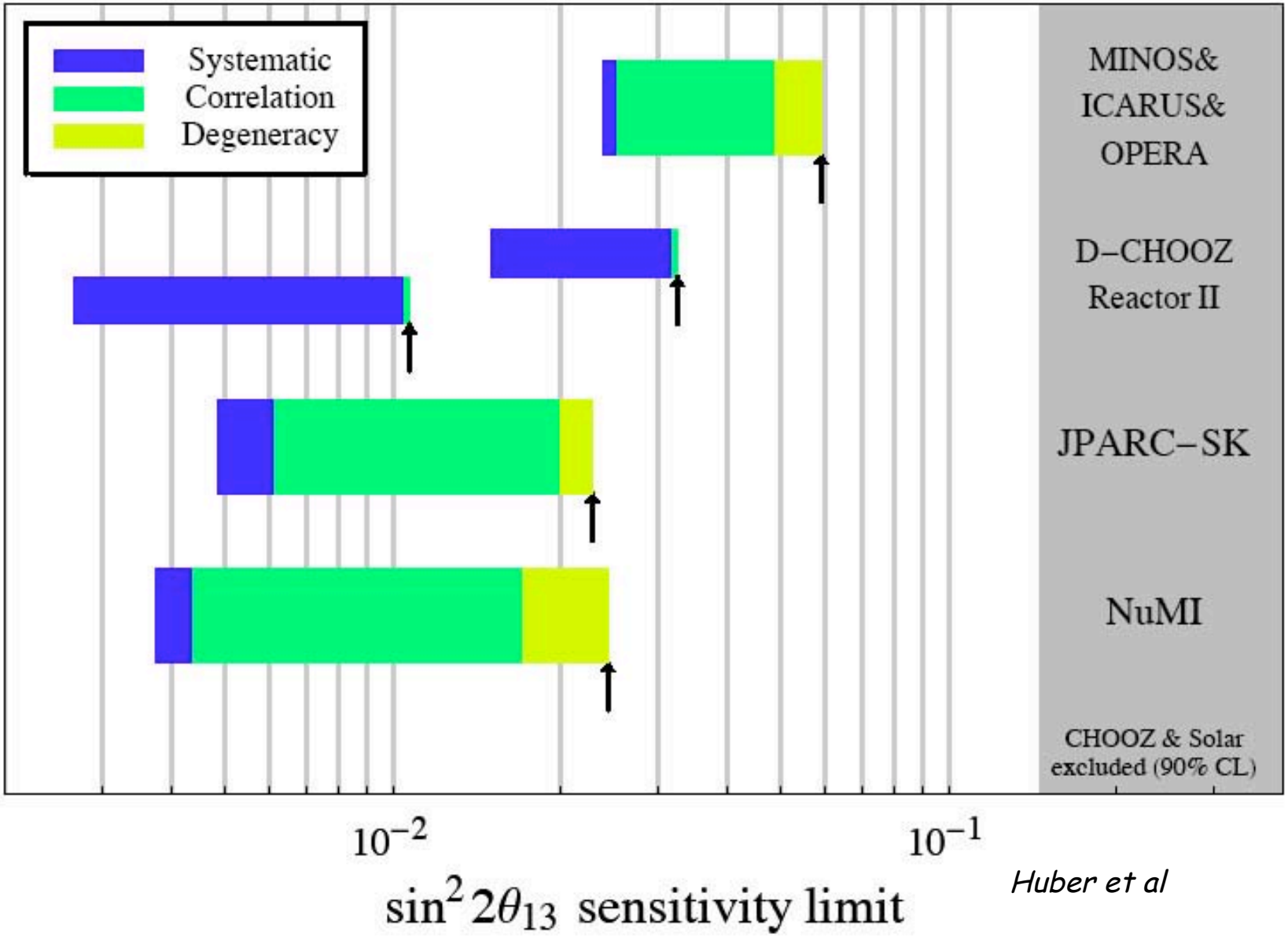
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

•A timely accelerator experiment with comparable $\sin^2 2\theta_{13}$ sensitivity and sensitivity to the mass hierarchy through matter effects.



- appearance experiment $\nu_\mu \rightarrow \nu_e$
- measurement of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ yields θ_{13}, δ_{CP}
- baseline *O(100 -1000 km),* matter effects present

$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \ldots$$


Systematic
Correlation
Degeneracy
MINOS&
ICARUS&
OPERA
D–CHOOZ
Reactor II
JPARC–SK
NuMI
CHOOZ & Solar
excluded (90% CL)
10^{-2}
10^{-1}
$\sin^2 2\theta_{13}$ sensitivity limit

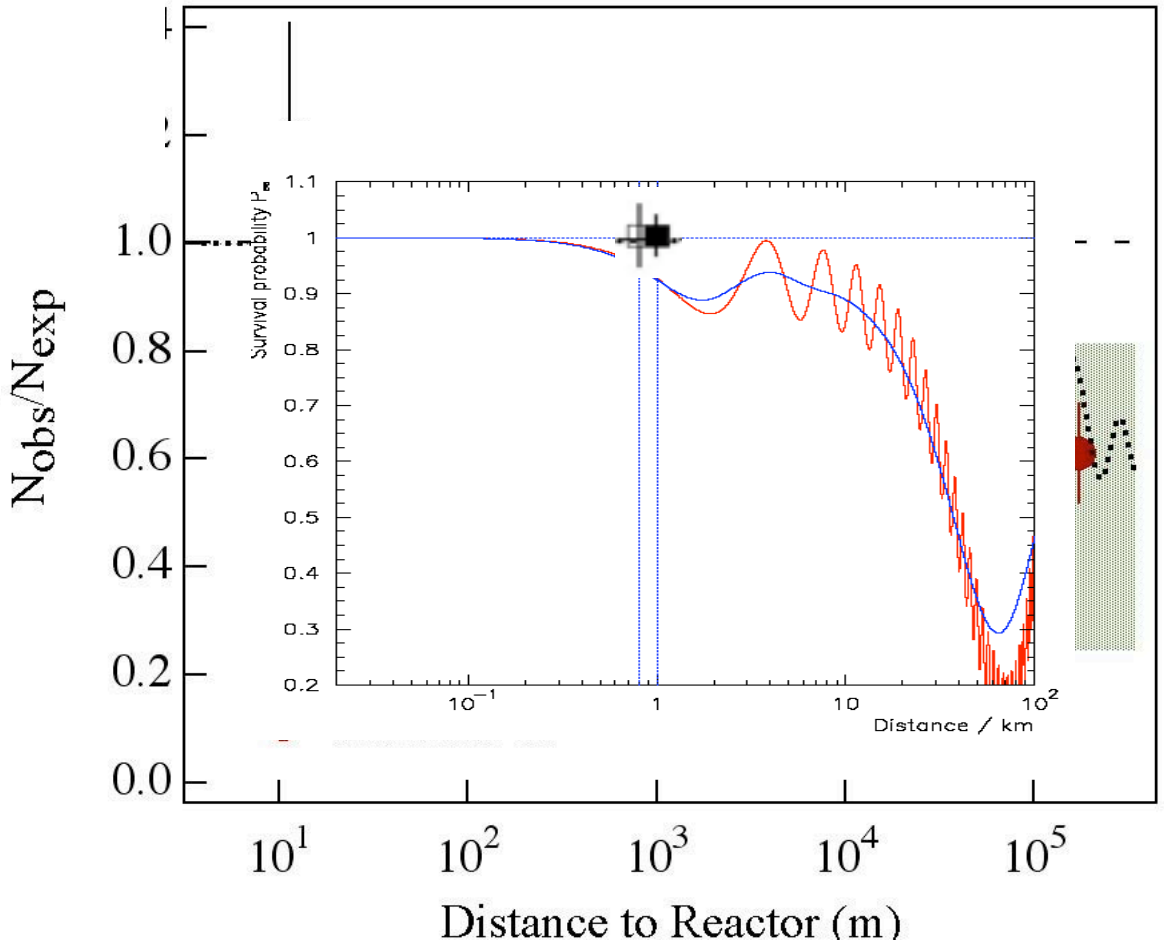
Huber et al

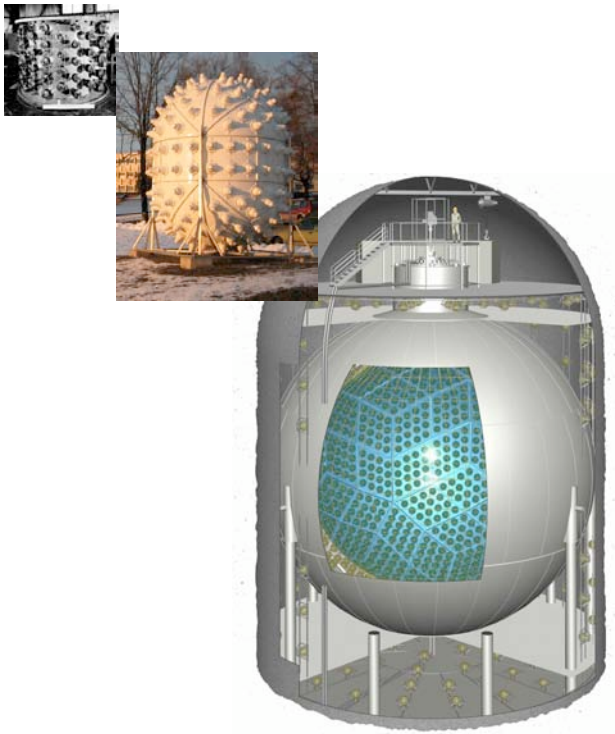
Reactor Anti-Neutrino Disappearance

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

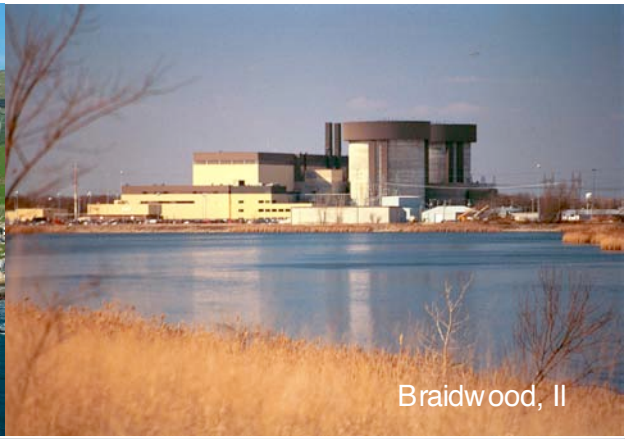
thermalization delay time

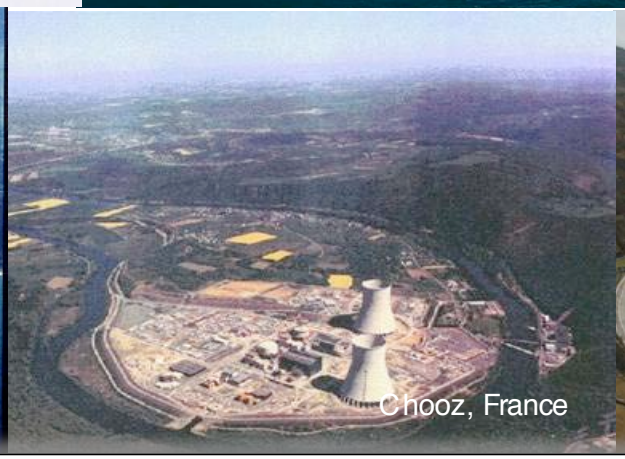
$$n + A \rightarrow A' + gammas$$

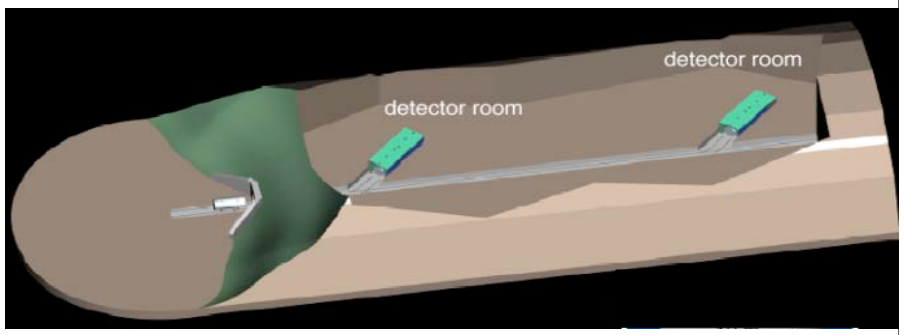




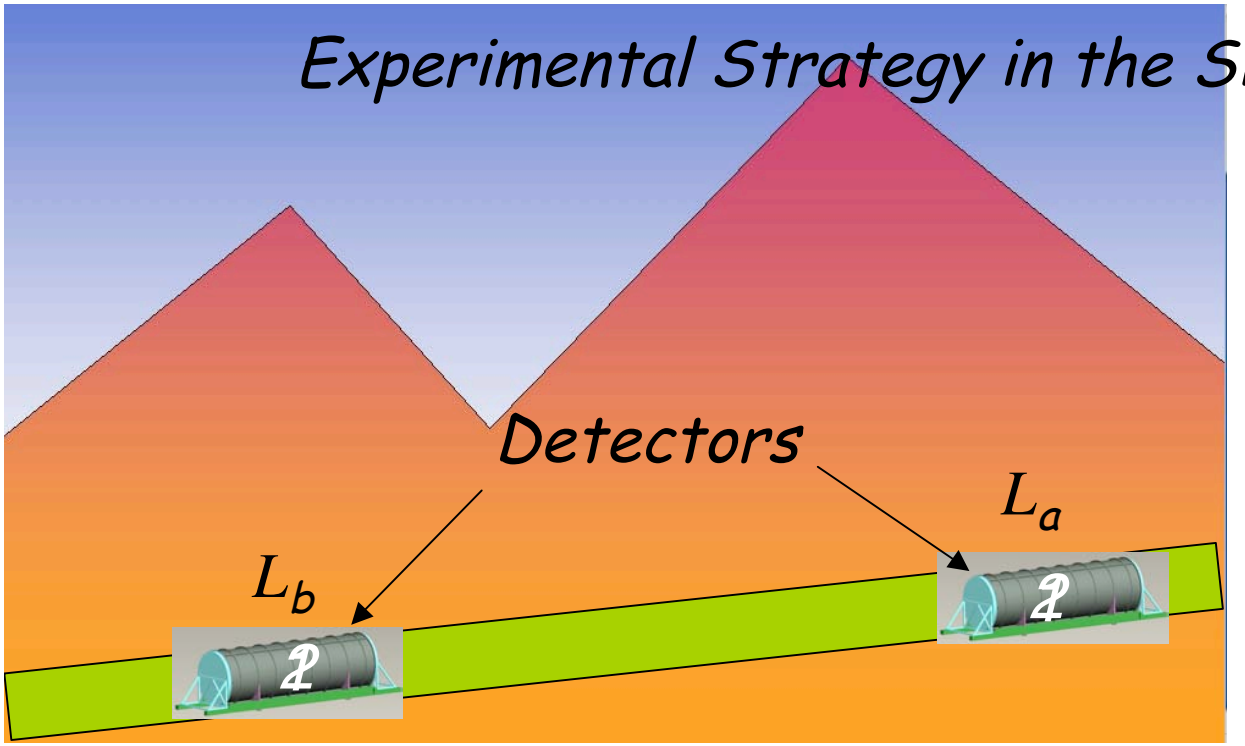
Many proposed sites for new reactor experiments



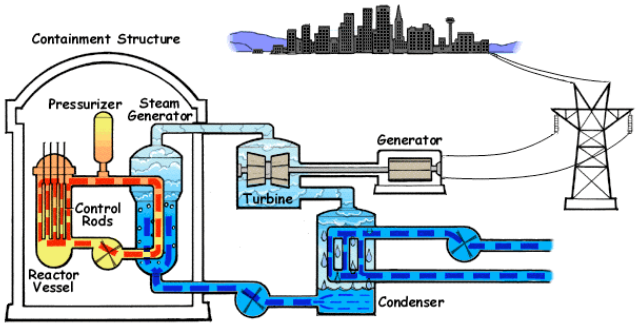




Experimental Strategy in the Simplest Case



San Luis Obispo
or Hong Kong

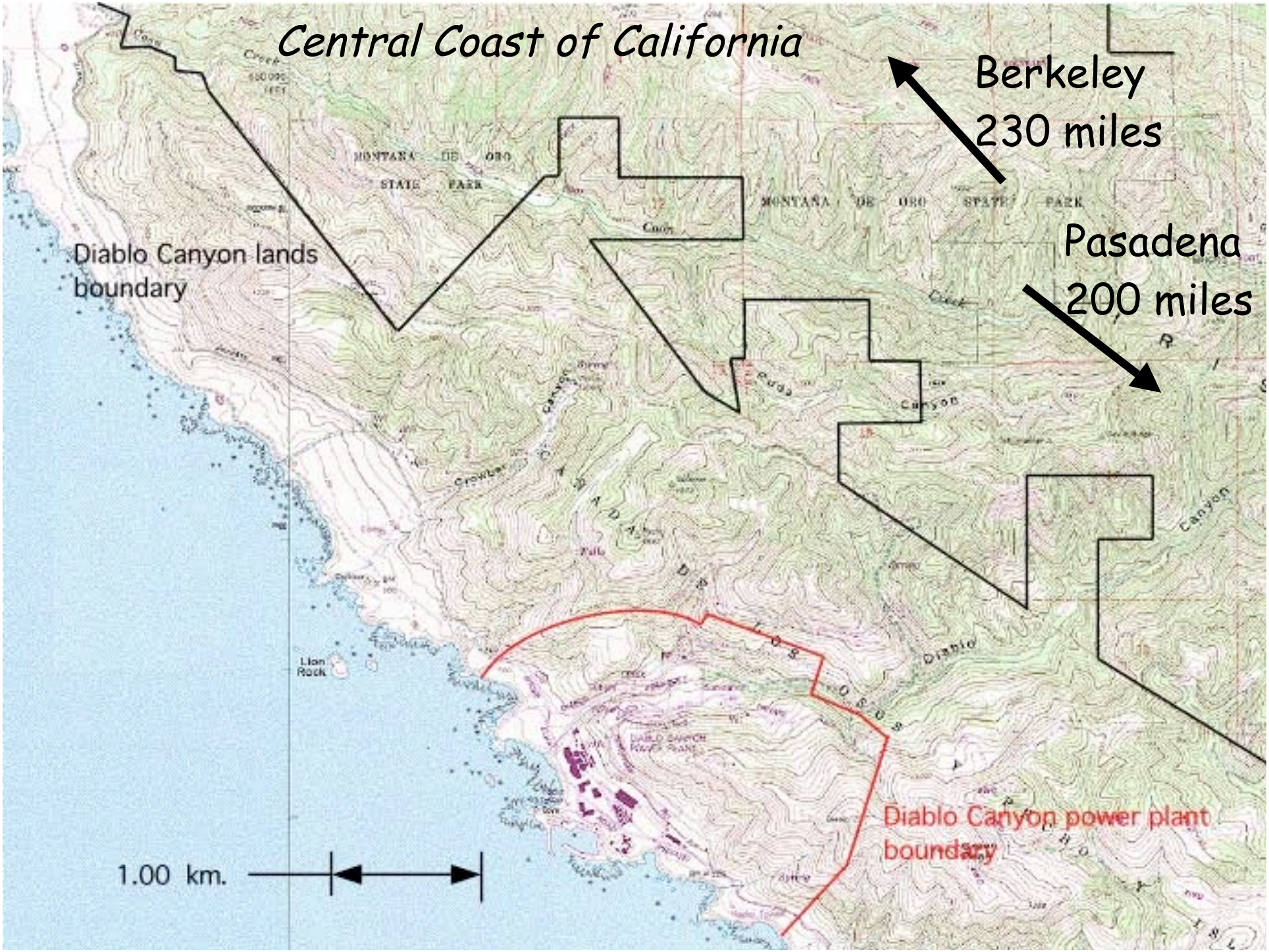


Reactor

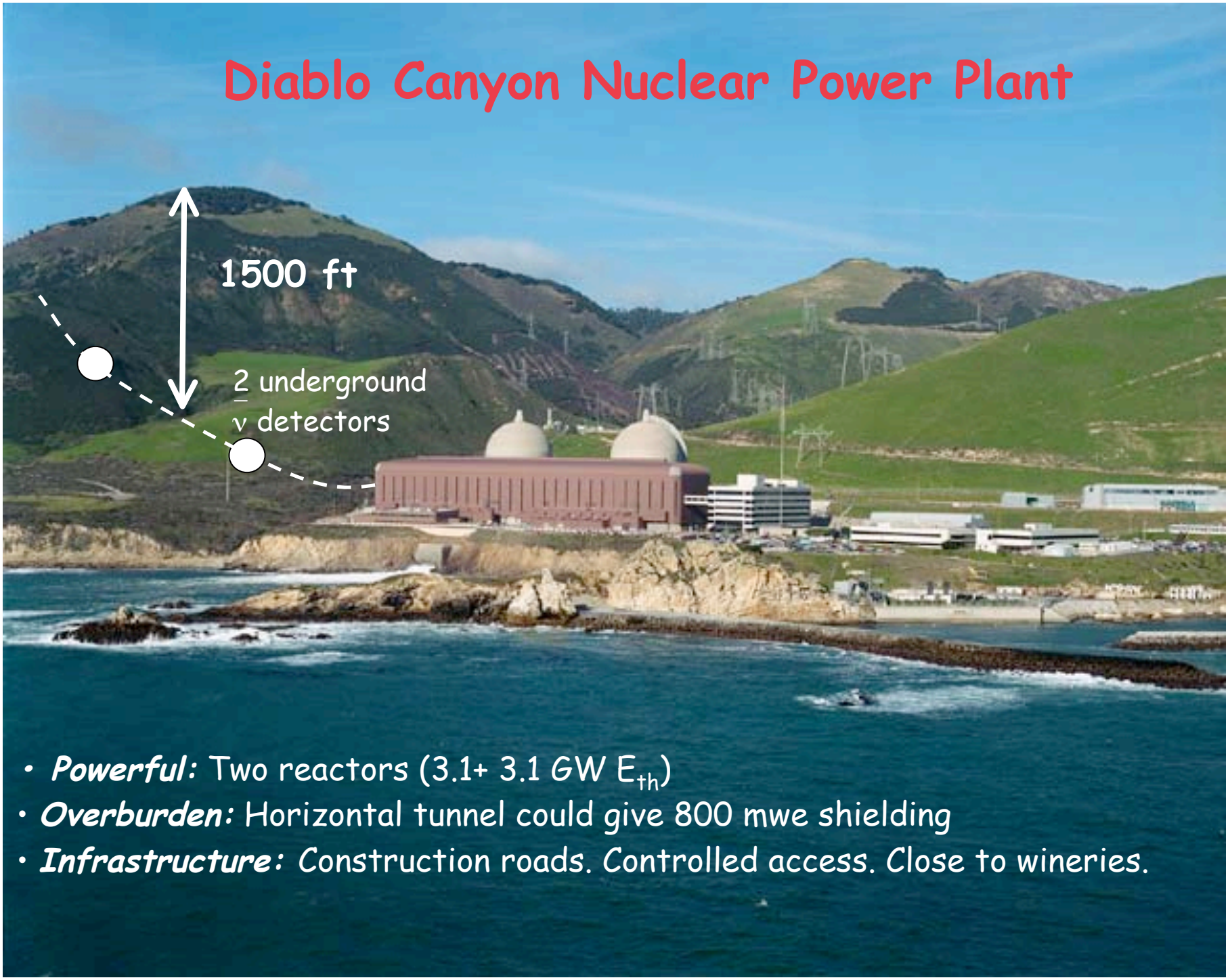
$$R_{1aA} = \frac{F_A}{4\pi L_a^2}\varepsilon_1(1-\delta_a)$$

$$\frac{R_{1aA}}{R_{2bA}}\frac{R_{2aB}}{R_{1bB}} = \frac{L_b^{\,4}}{L_a^{\,4}}\frac{(1-\delta_a)^2}{(1-\delta_b)^2} \approx \frac{L_b^{\,4}}{L_a^{\,4}}\left[1-2(\delta_a-\delta_b)\right]$$

$$(\delta_a-\delta_b) \approx \sin^2(2\theta_{13})\left[\sin^2(1.27\frac{\Delta m_{13}^2 L_a}{E}) - \sin^2(1.27\frac{\Delta m_{13}^2 L_b}{E})\right]$$


Central Coast of California
Berkeley
230 miles
Pasadena
200 miles
Diablo Canyon lands
boundary
Diablo Canyon power plant
boundary
1.00 km.

Diablo Canyon Nuclear Power Plant



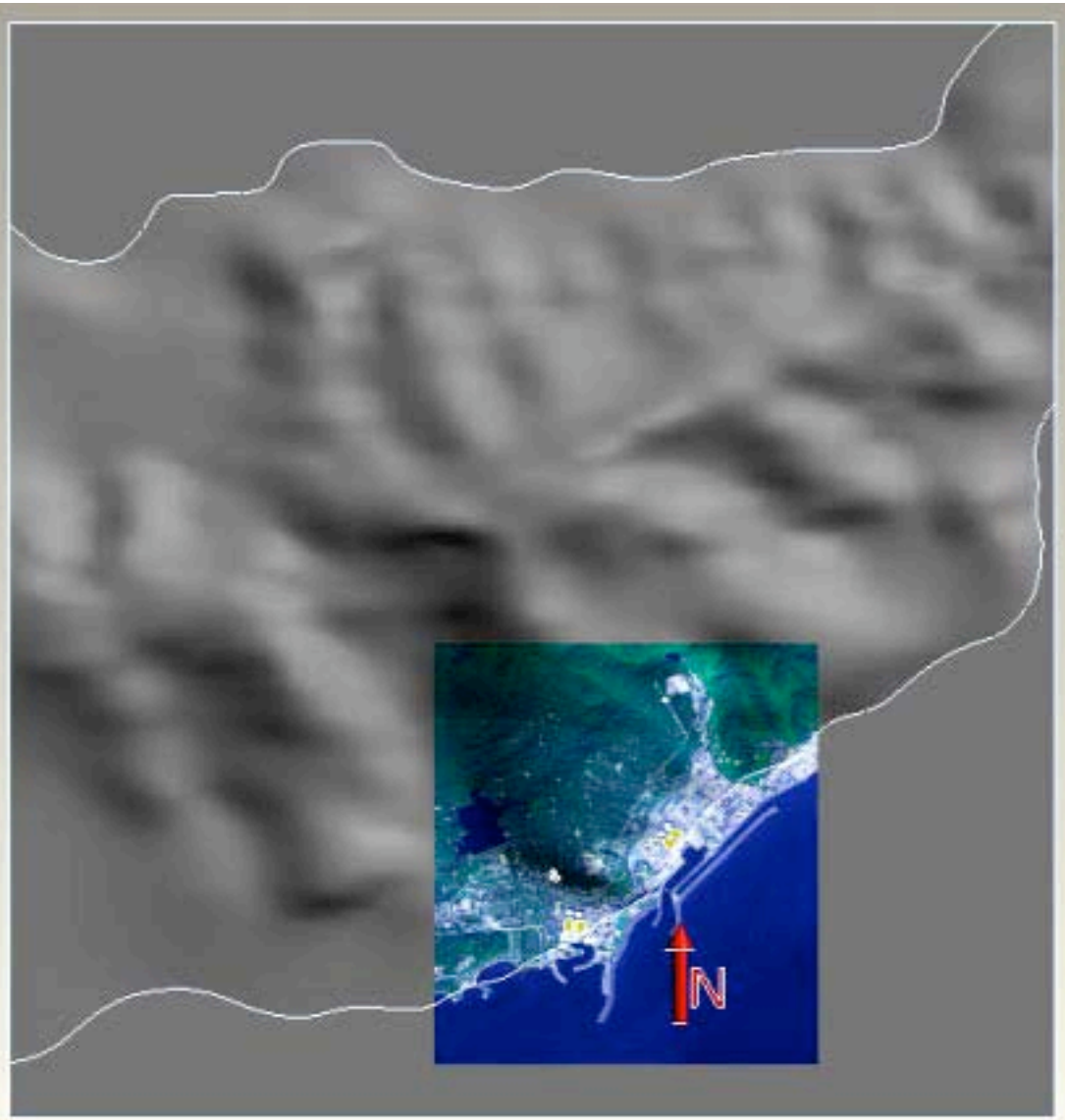
- ***Powerful:*** Two reactors (3.1+ 3.1 GW E_{th})
- ***Overburden:*** Horizontal tunnel could give 800 mwe shielding
- ***Infrastructure:*** Construction roads. Controlled access. Close to wineries.

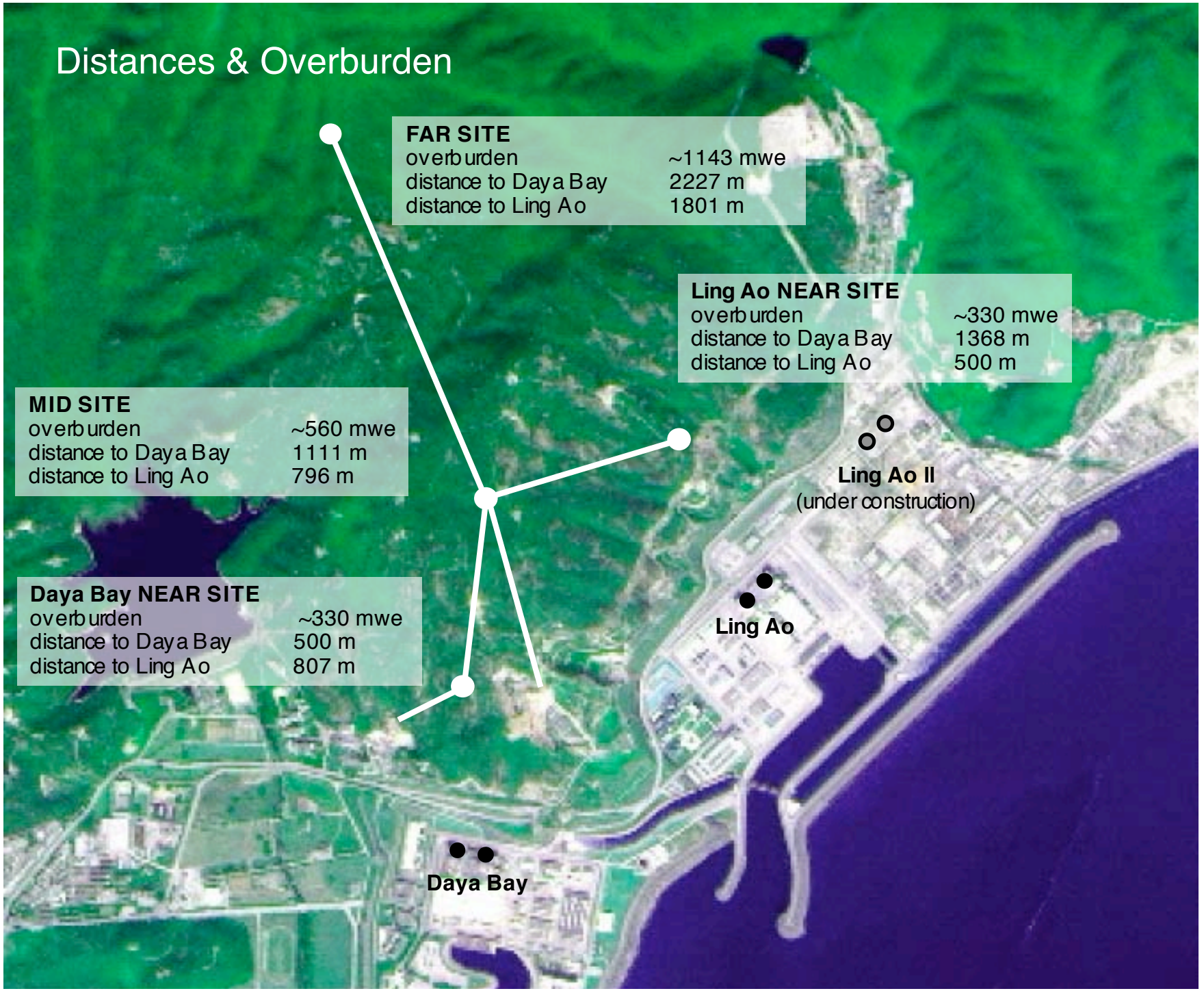
Niudipu
Longhua
Buji
Henggang
Kuiyong
Dapeng
Yantian
Daya Bay
Shenzhen
Sha Tau Kok
Shatoujiao
Tai Pang Wan
Tong O
Man Uk Pin
Pak Shek Au
Tung Wan
Fanling
Lai Tau Shek
Cheung Wo
22°
Tin San Wai
Ting Kok
Shuen Wan
Berkeley
6,907 miles
Kau Lau Wan
Yung Shue Au
Tai Po
XIAOSANMEN DAO
Wu Lei Kiu
Lin Fa Tei
Wu Kwai Sha
HONG KONG SAR (CHINA)
Wong Yi Chau
Tsuen Wan
Sha Tsiu
Sai Kung
Pak A
Pik Uk
Fu Tau Pun Chau
Cheung Sha Wan
Kai Tak International Airport
Tau Kwu
Kowloon
Yau Tong
KENNEDY TOWN
HAPPY VALLEY
Victoria Peak 554 m (1818 ft)
Hong Kong
Mount Collinson
Stanley Mount
South China Sea
Fa Peng

Daya Bay/Ling Ao Nuclear Power Plant

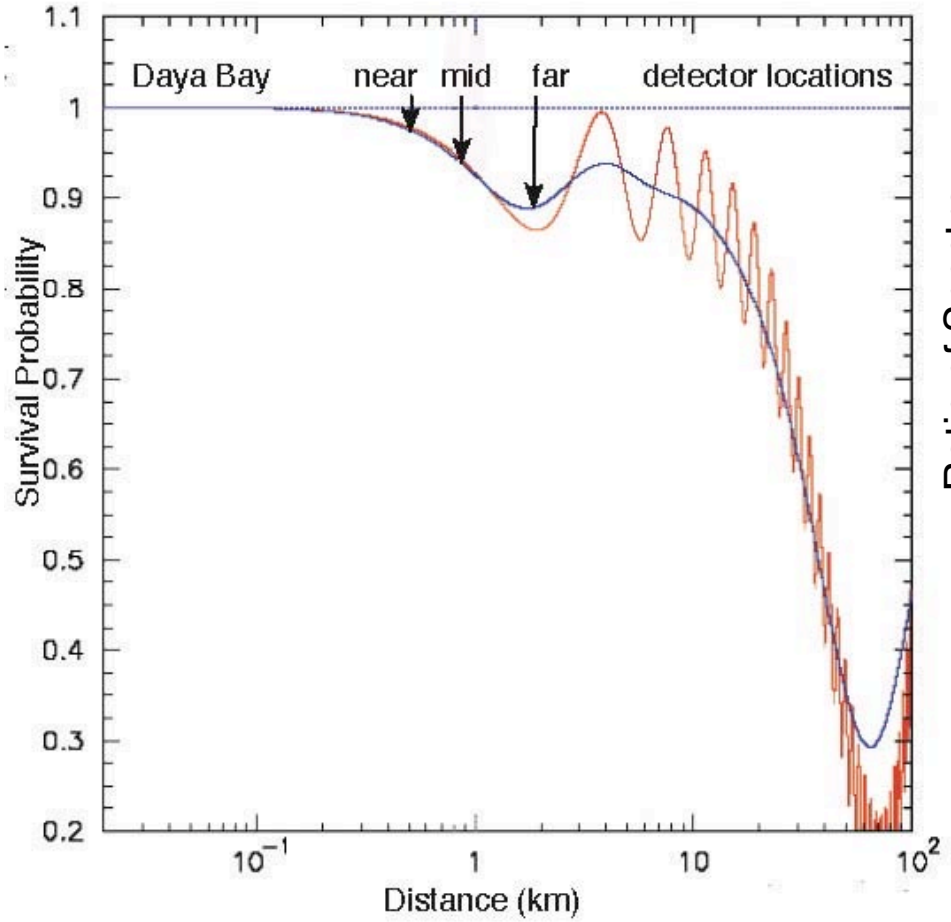
- ***Powerful:*** Four reactors (4 units 11.6 GW E_{th} Eventually 6 units 17.4 GW E_{th})
- ***Overburden:*** Horizontal tunnel could give 1100 mwe shielding
- ***Infrastructure:*** Construction roads. Controlled access. Not close to wineries.

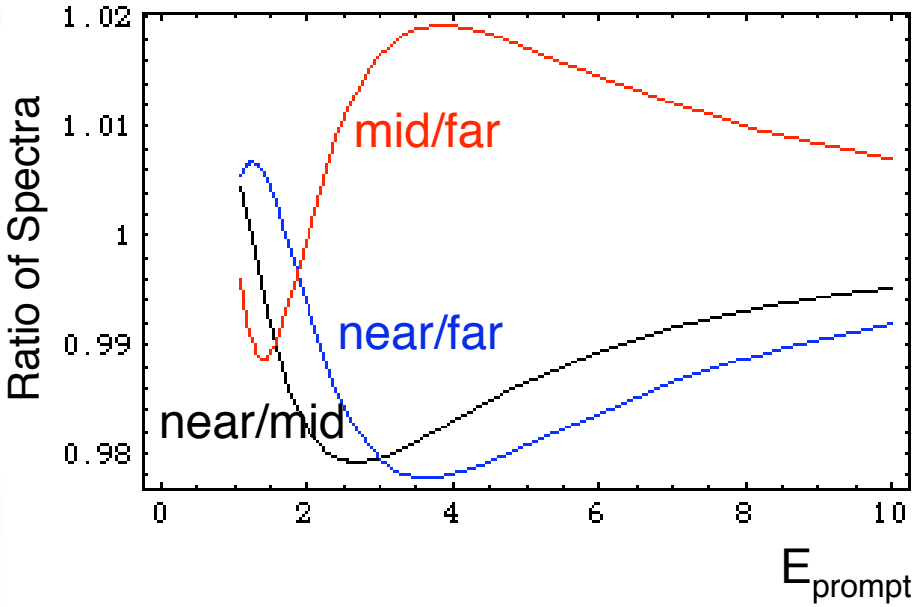
Welcome to Daya Bay




Distances & Overburden
FAR SITE
overburden ~1143 mwe
distance to Daya Bay 2227 m
distance to Ling Ao 1801 m
Ling Ao NEAR SITE
overburden ~330 mwe
distance to Daya Bay 1368 m
distance to Ling Ao 500 m
MID SITE
overburden ~560 mwe
distance to Daya Bay 1111 m
distance to Ling Ao 796 m
Daya Bay NEAR SITE
overburden ~330 mwe
distance to Daya Bay 500 m
distance to Ling Ao 807 m
Ling Ao II
(under construction)
Ling Ao
Daya Bay

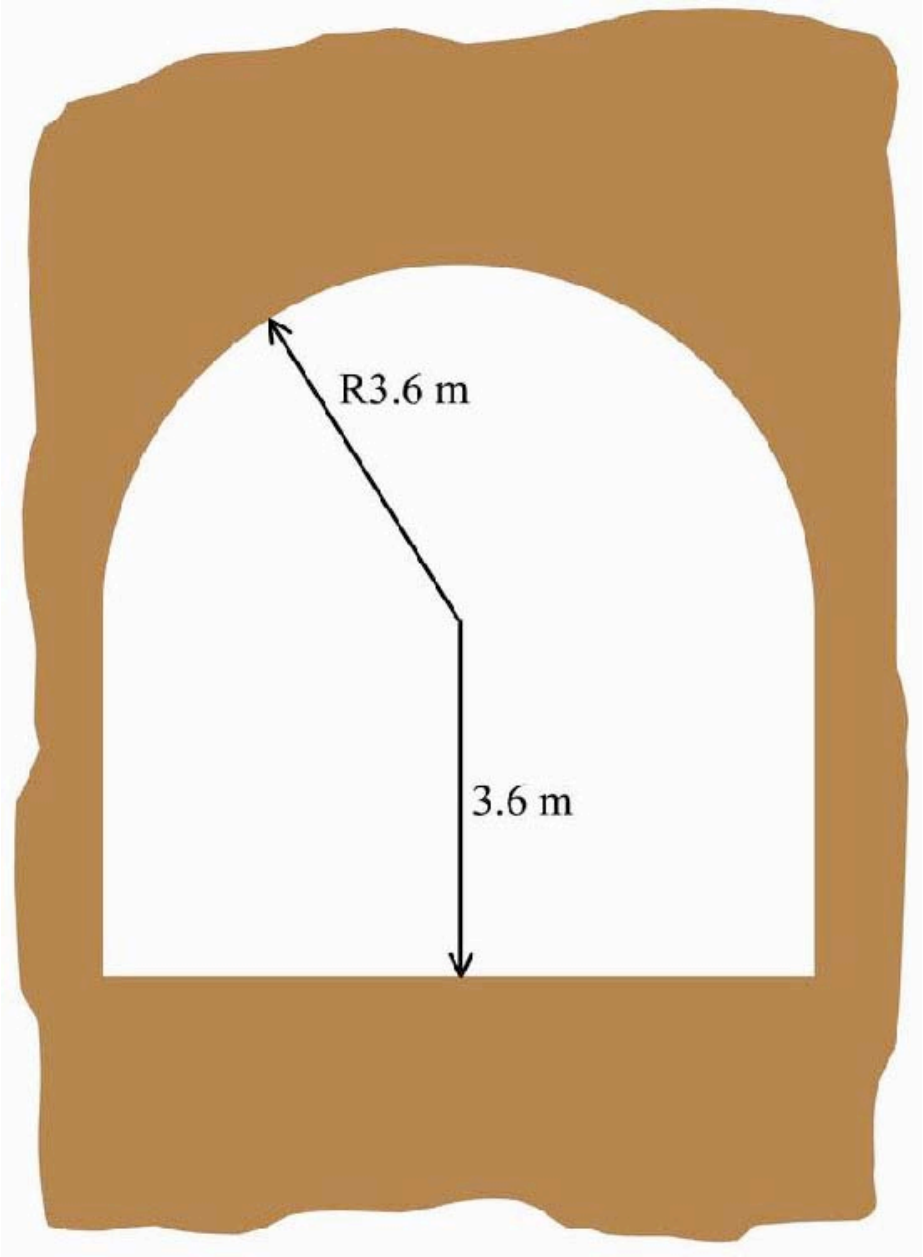
Spectral Distortions with 3 Baselines





- 3 baselines provide consistency checks and eliminate single point failure of experiment, in particular if the backgrounds too high in near detector or unaccounted systematics in one of detectors

Significant tunnels already exist at the Daya Bay site



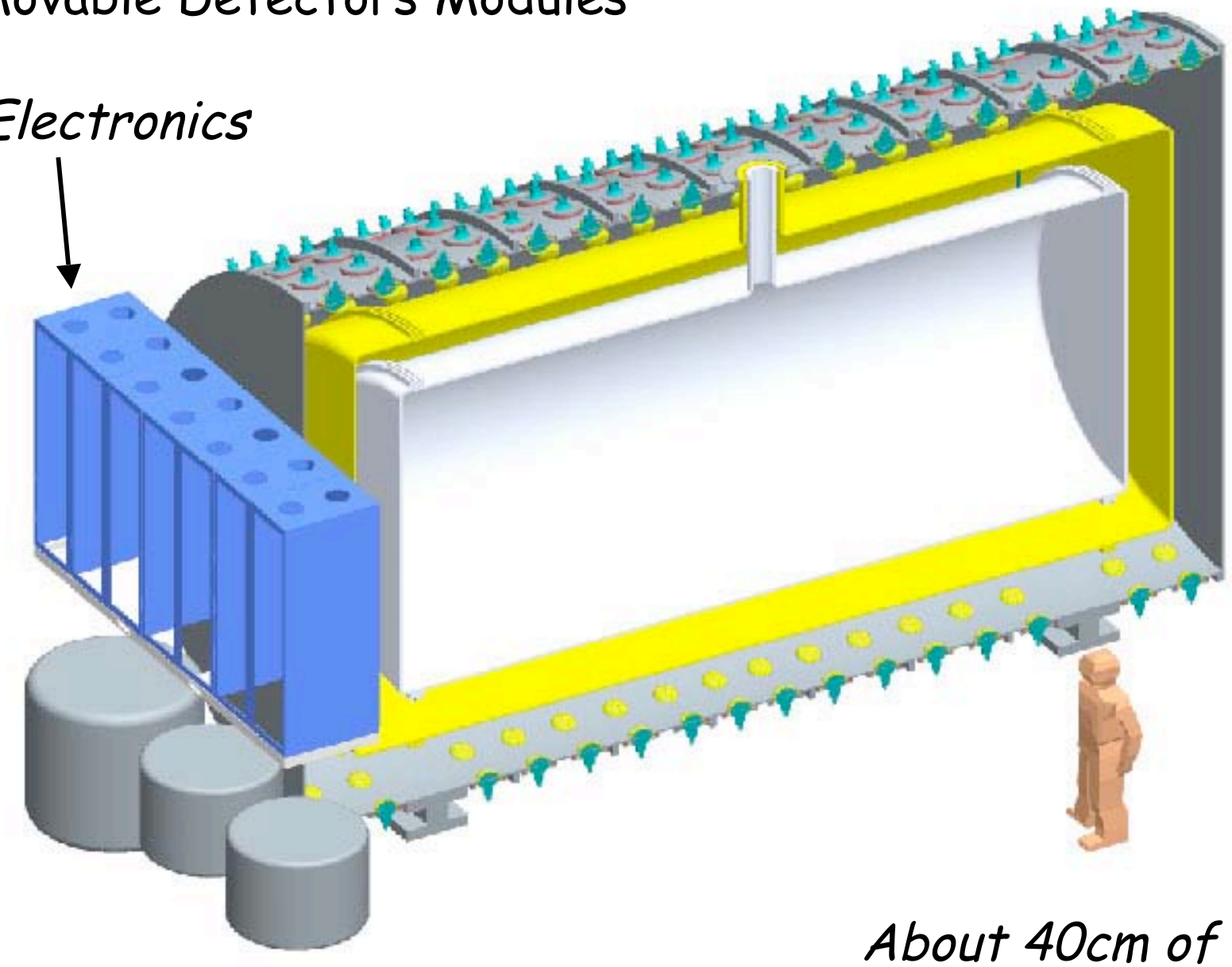
On site service tunnel near DB reactor

1.5 km single lane tunnel at site

Daya Bay quarry will be filled with the tailings

1/2 of waste rock is used for overburden

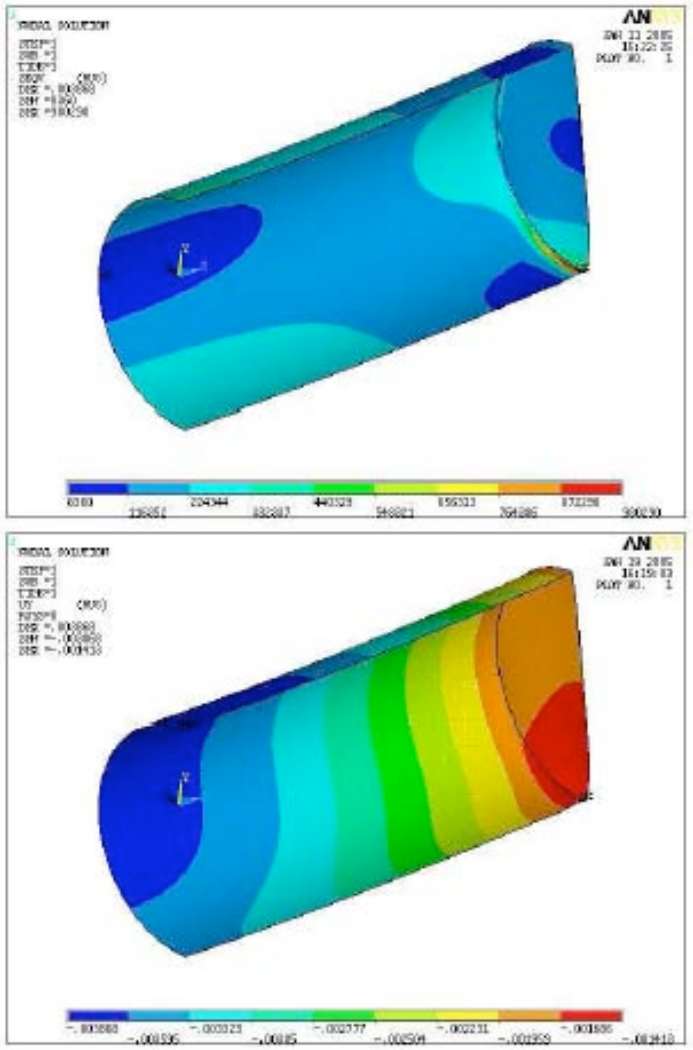
Movable Detectors Modules



40 ton FV PMTs on Barrel

About 40cm of oil buffer to reduce bgds

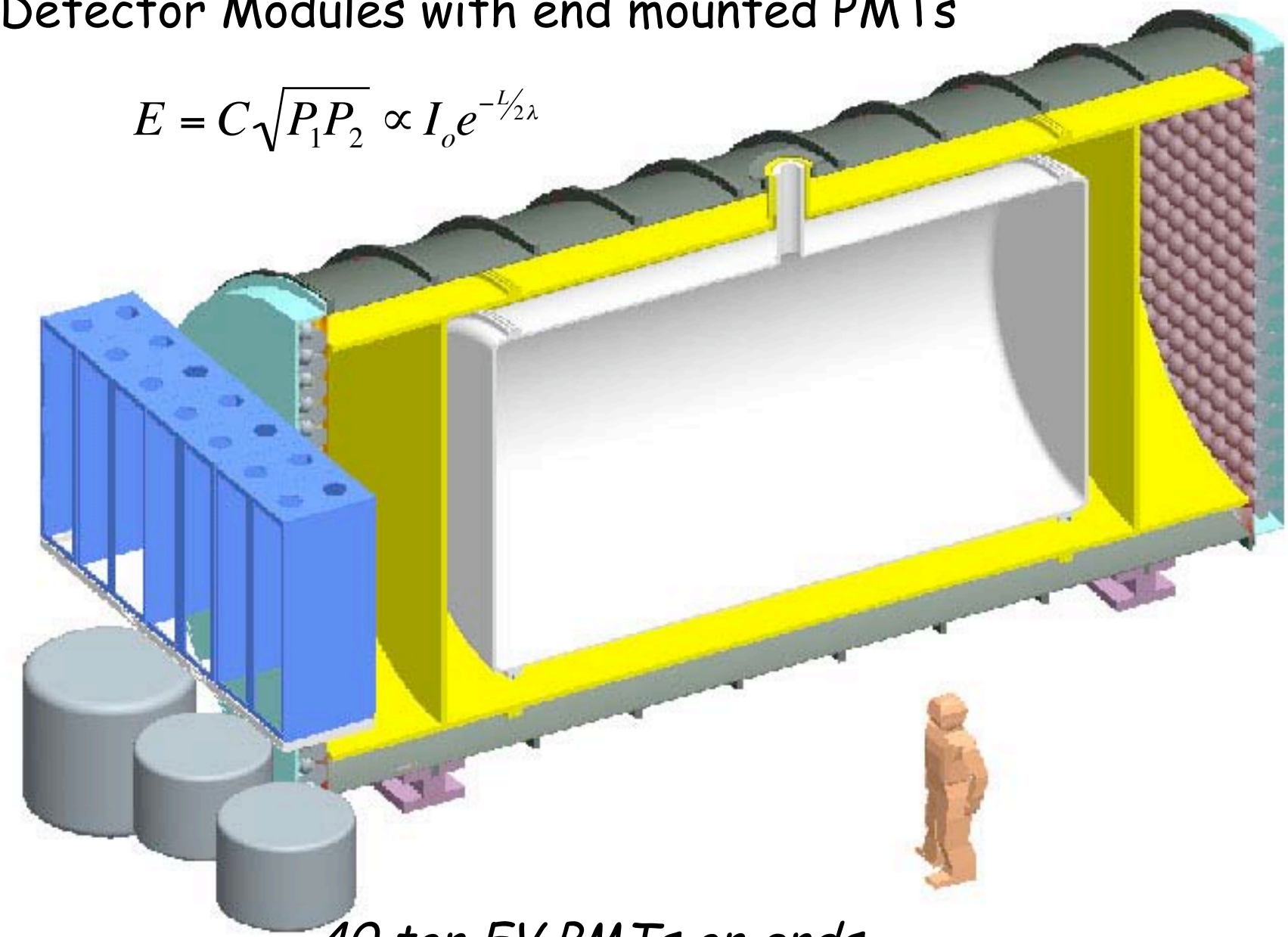
Manufactures have experience with large double walled acrylic structures



Stress Analysis of acrylic

Detector Modules with end mounted PMTs

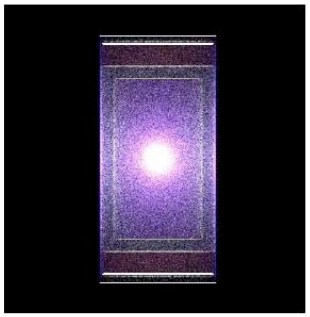
$$E = C\sqrt{P_1 P_2} \propto I_o e^{-L/2\lambda}$$



40 ton FV PMTs on ends

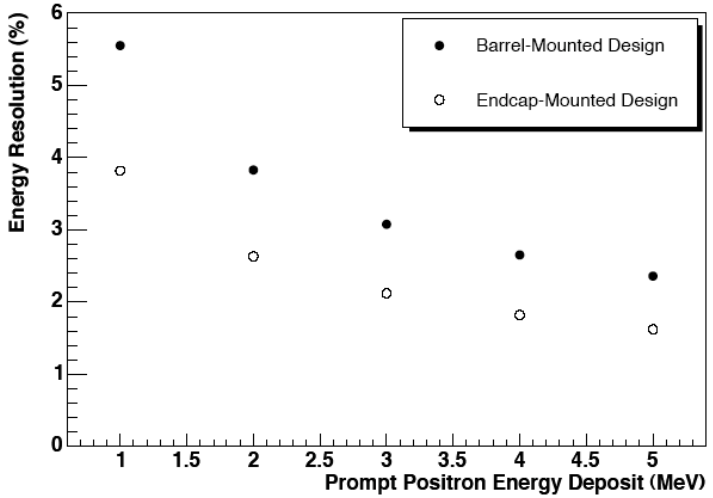
Monte Carlo evaluation of detector designs

Barrel-Mounted

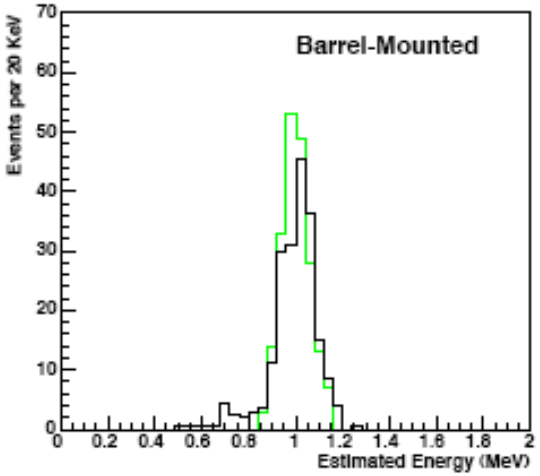


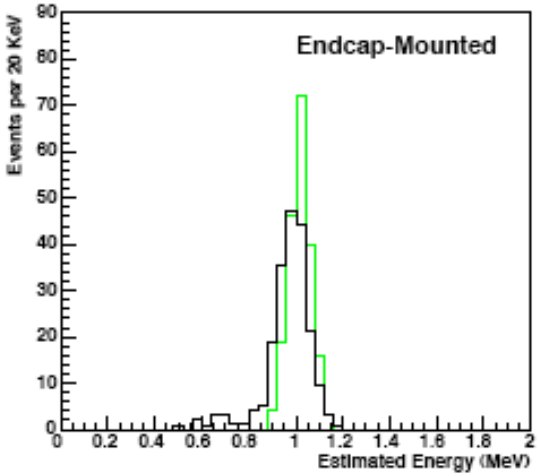
Endcap-Mounted

Response to Positrons



Response to 2x0.511 MeV





Locomotion with commercially available airplane tugs

Problem: transport ~150 ton detectors in 1-2 km long tunnels

Ingersoll-Rand T-350
- 35,000 lb draw bar pull
- 6 cylinder diesel, 192 hp
- 16.5 feet long, 8 feet wide, 8.5 feet tall

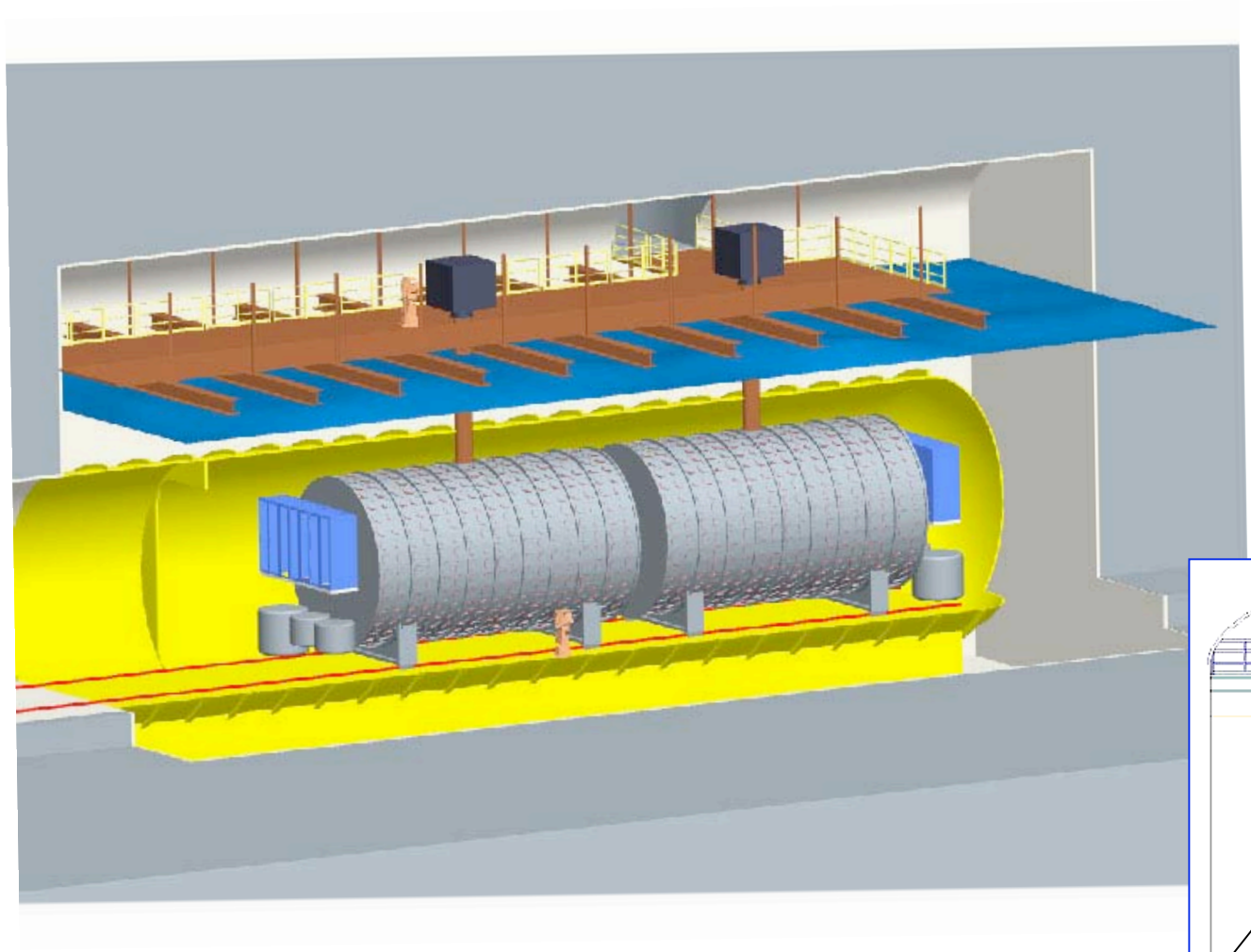
Hough TD-500
- up to 747s
- 50,000 lb draw bar pull
- 8 cylinder diesel engine
- 65,000 lbs
- 26 feet long, 9 feet wide, 5 feet tall

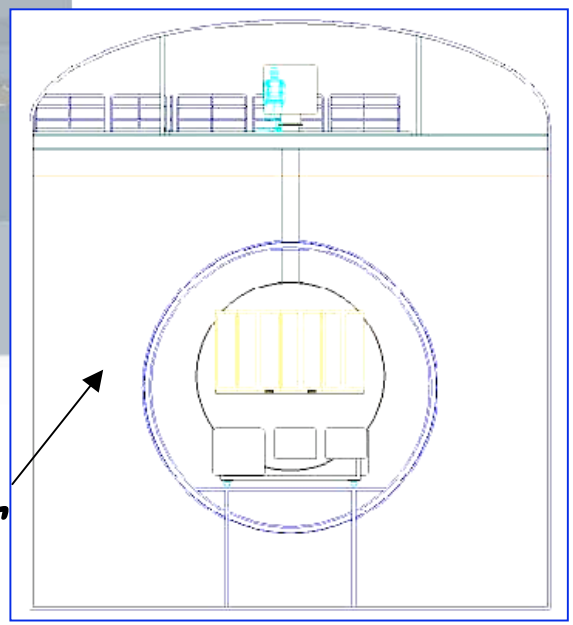
Stewart and Stevenson GT-110
- 78,000 lb draw bar pull for gross vehicle weights up to 120,000 lb
- 6 cylinder diesel engine, 255 hp, 700 lb-ft max torque
- 4 forward gears, 3 reverse gears
- 5 mph @ 17,500 drawer bar pull (3rd gear); max is 13.5 mph

Electrically powered Tractors

Solution: Hilman rollers with Accu-Roll guidance system and tugs.

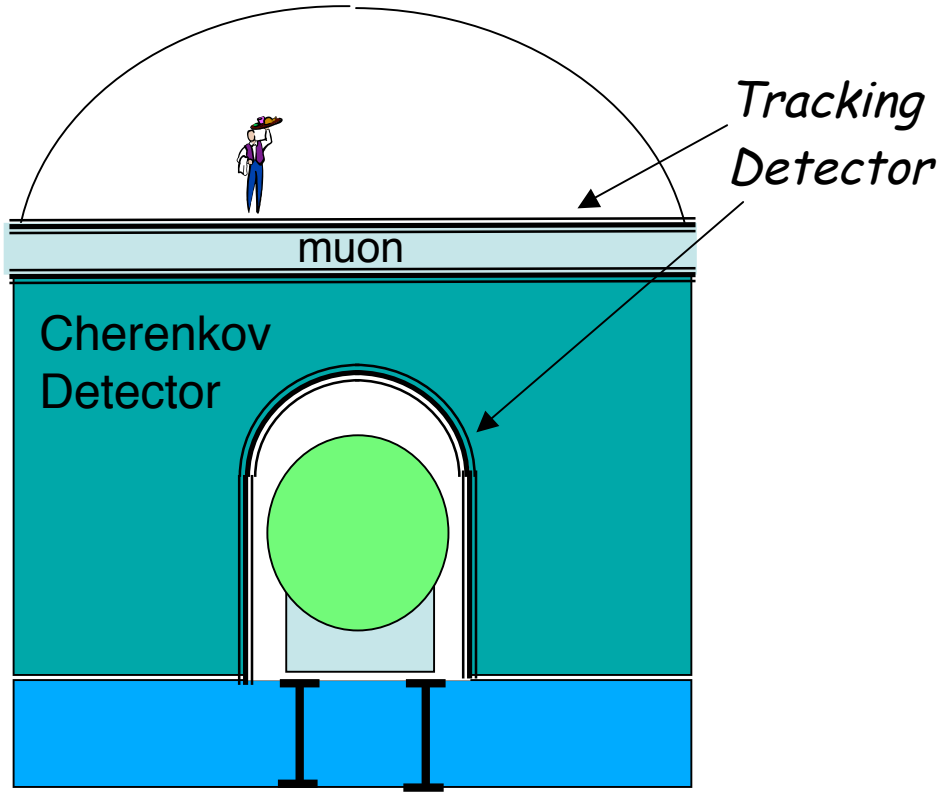
Detector Halls (Water Rooms)

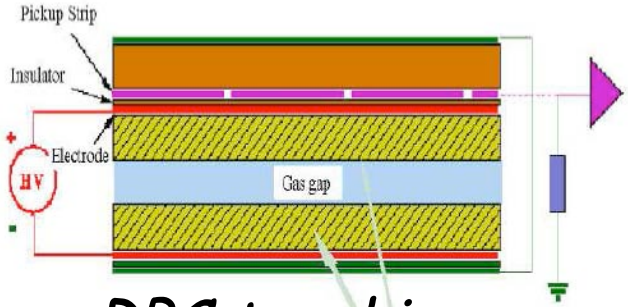




Water

Muon Veto





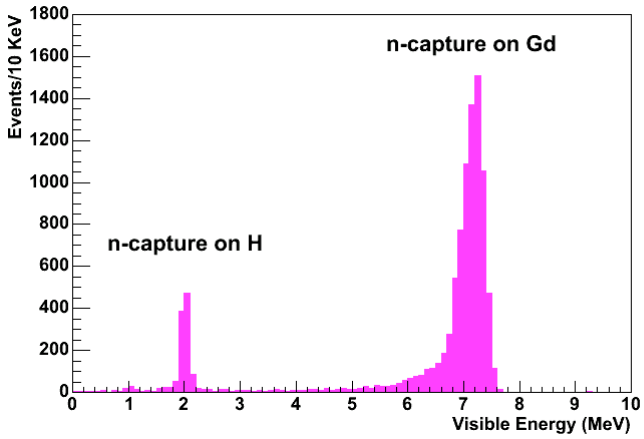
RPC tracking

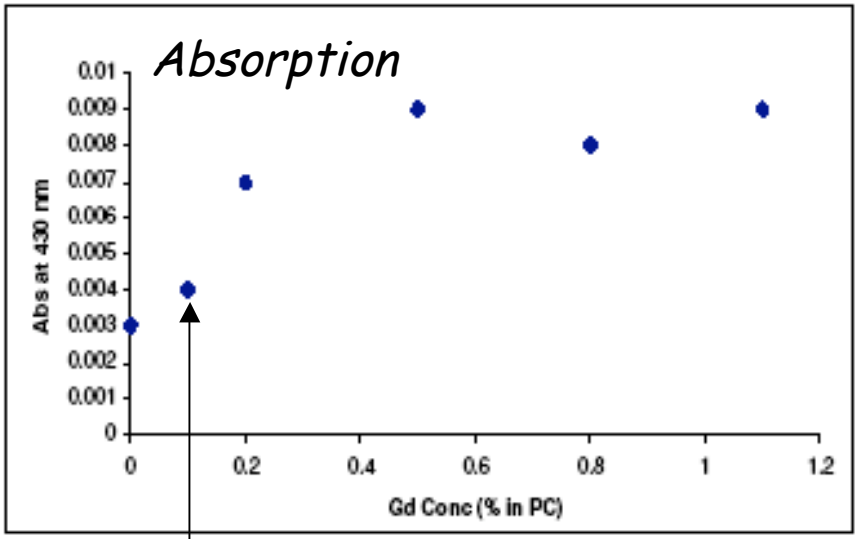
MINOS extruded Scintillators

Liquid Scintillator

- Gd-loaded LS: $\sigma_{capture}$ ~ 40,000 barns, E_γ~8 MeV R&D to find stable 0.1% mixture underway at BNL and IHEP

- Chooz and Palo Verde used Gd dissoved in alcohol. Found to be unstable.
- The BNL group is working with carboxylic acid produced metal-organo chemical complexes dissolve in LS producing stable mixtures. Attenuation lengths of ~ 10 m and no degradation over many months of aging tests made so far.

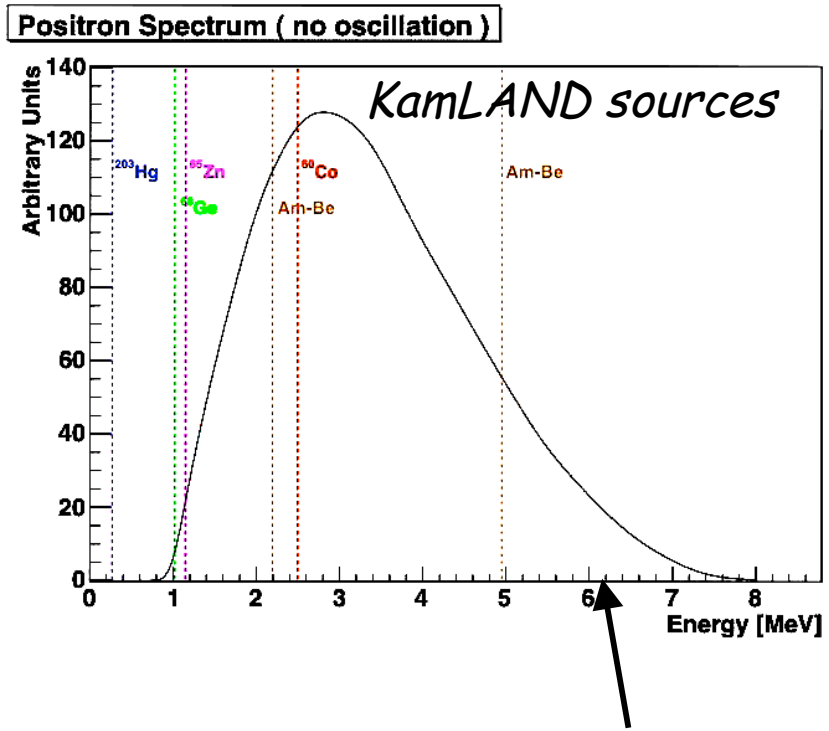




λ ~ 10 m

Calibration

• A rigorous and well formulated calibration program is essential to a successful reactor experiment.



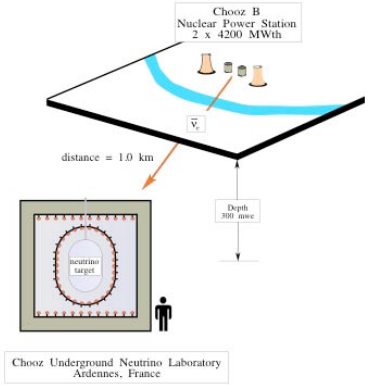
A novel ^{16}N source is under development

- *Gamma ray calibration sources with an empirically supported connection to positron energy deposition.*
- *Neutron sources*
- *lasers and LEDs*
- *electron and positron sources*
- *Spallation produced products: 12B, n-capture reactions.*

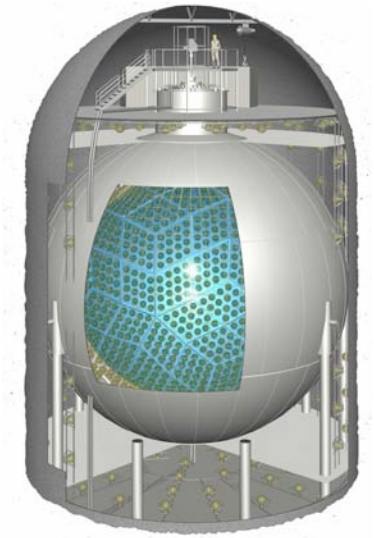
Backgrounds

• Uncorrelated backgrounds from radioisotope contamination and residual muon produced spallation products.

• Correlated backgrounds from moun produced fast neutrons and beta delayed neutron decaying isotopes.



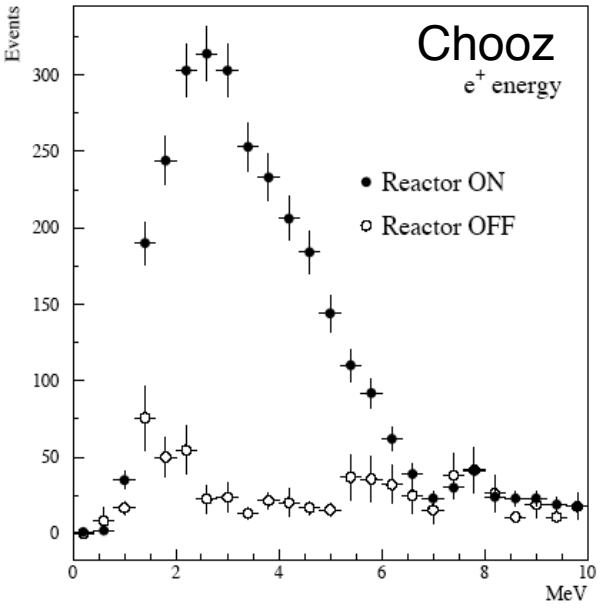
CHOOZ
~5 tons
~300 mwe
~25 $\bar{\nu}_e$/day



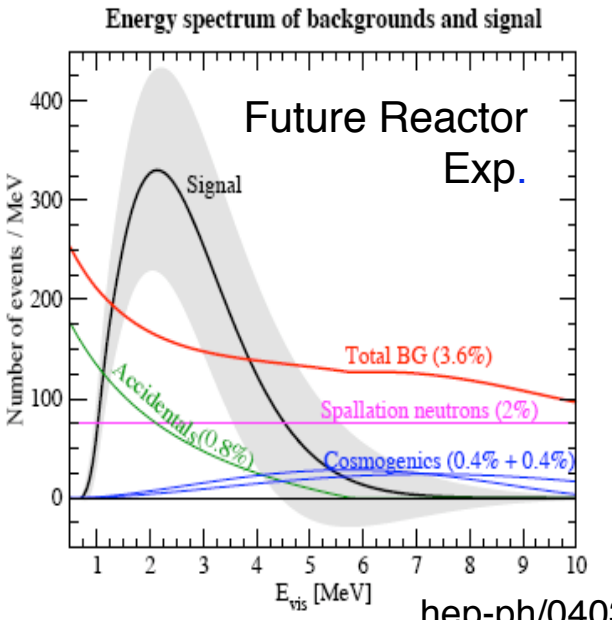
KamLAND
~ 1000 tons
~ 2700 mwe
~0.3 $\bar{\nu}_e$/day

Much can be learned about the backgrounds from the experiences of the previous monolithic detectors

Inconsistencies in the estimates of ^{9}Li Backgrounds



hep-ph/030107

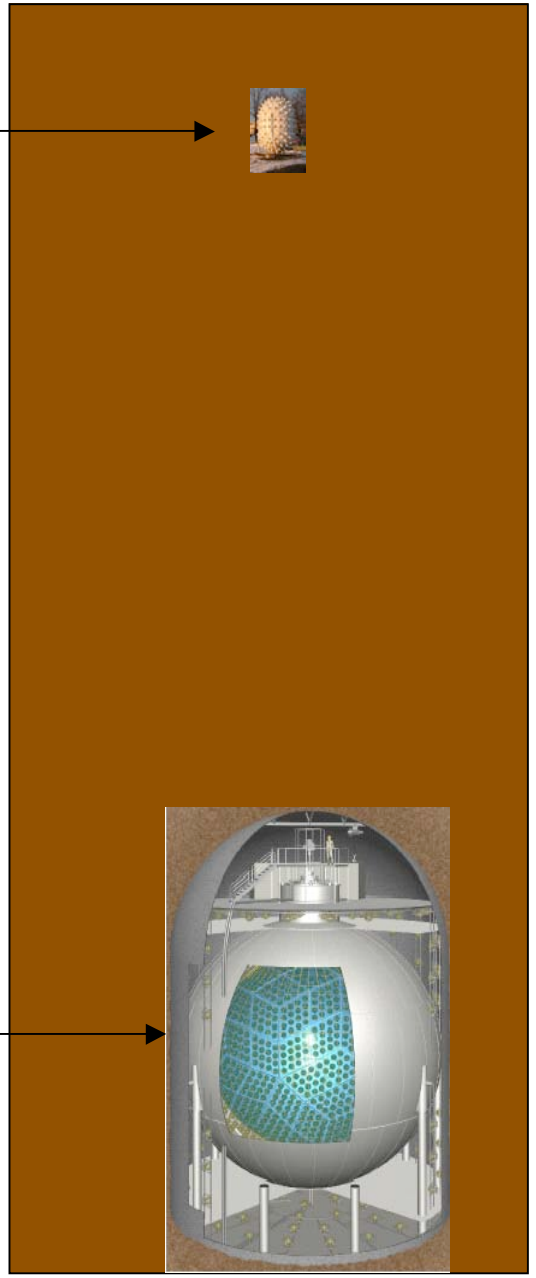


hep-ph/0403068

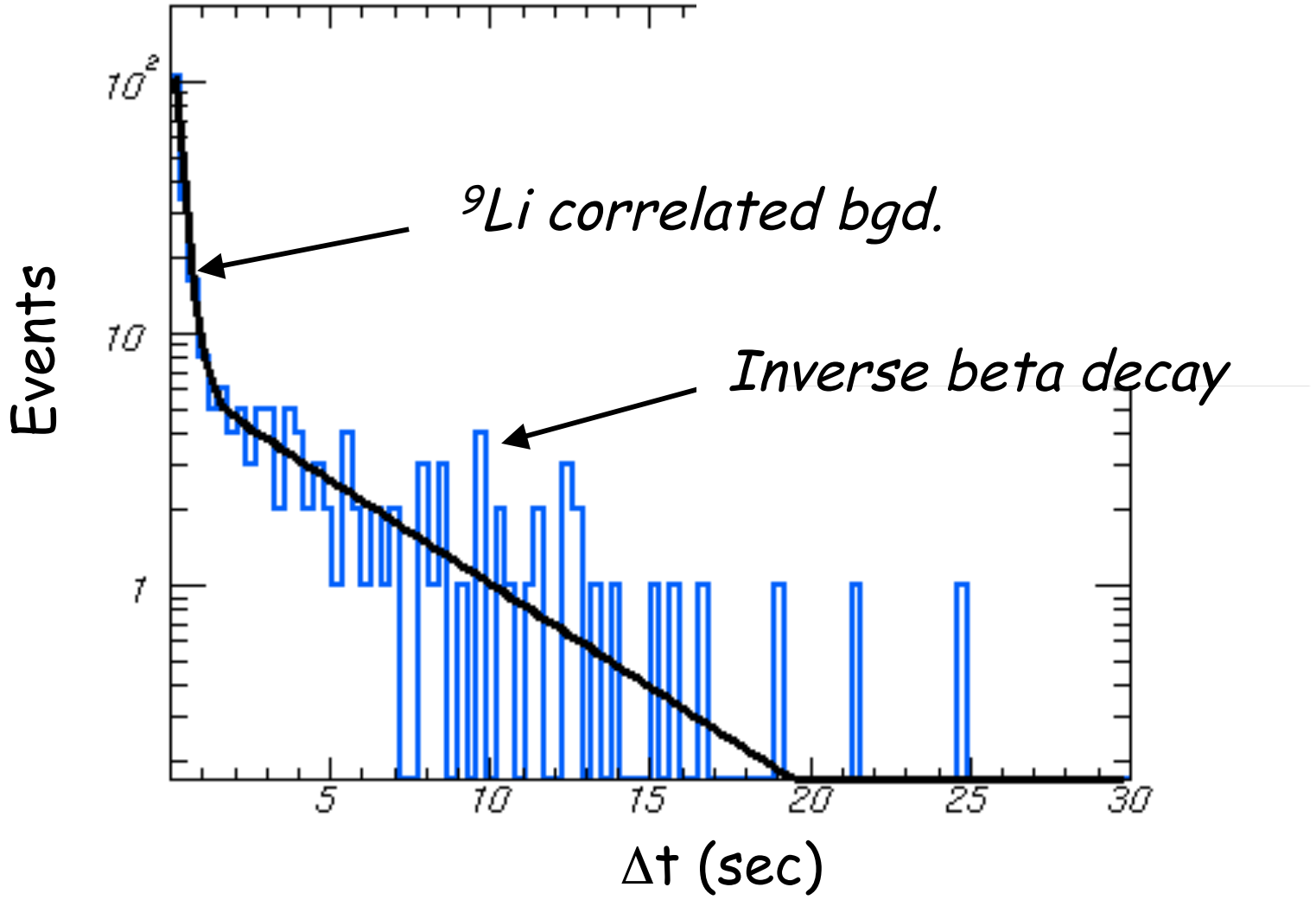
300 mwe

Scaling from KamLAND expect 3-4/day correlated bgd in CHOOZ--they saw ~2.5/day

2700 mwe



Time spectrum of neutrino candidates following muons



KamLAND Data

Staged Approach: Phase I Running

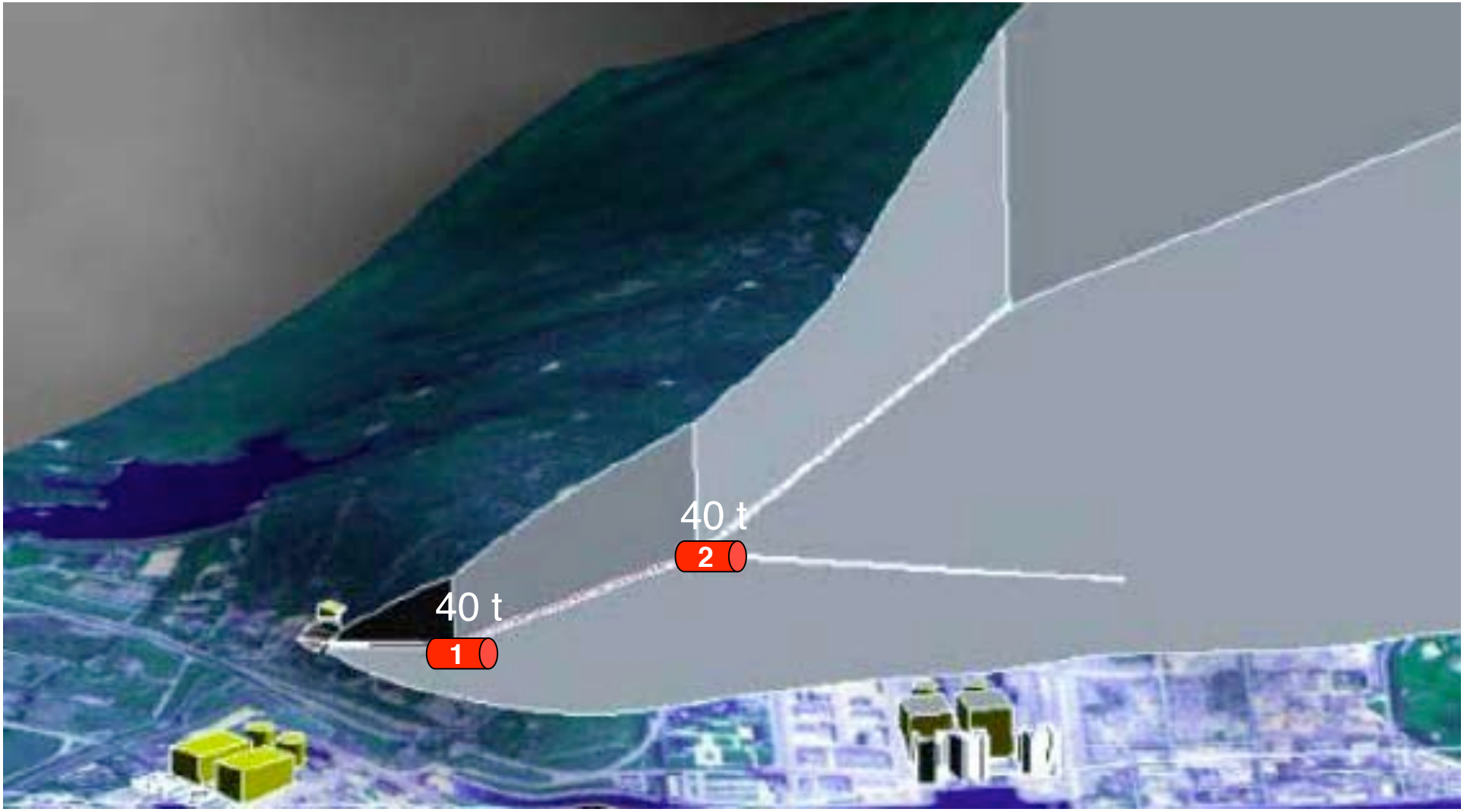


Illustration K. Chow

Deployment Strategy

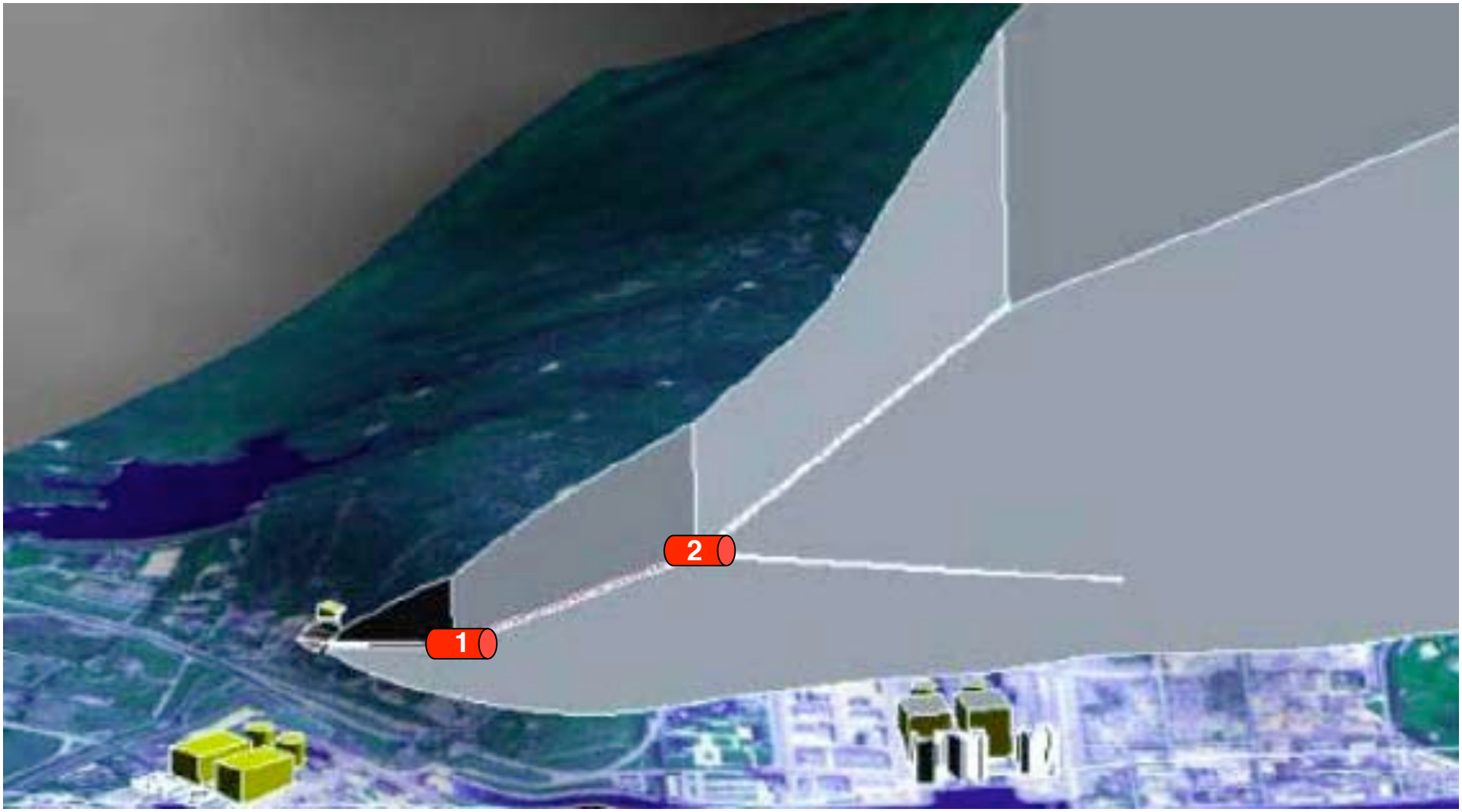


Illustration K. Chow

Deployment Strategy

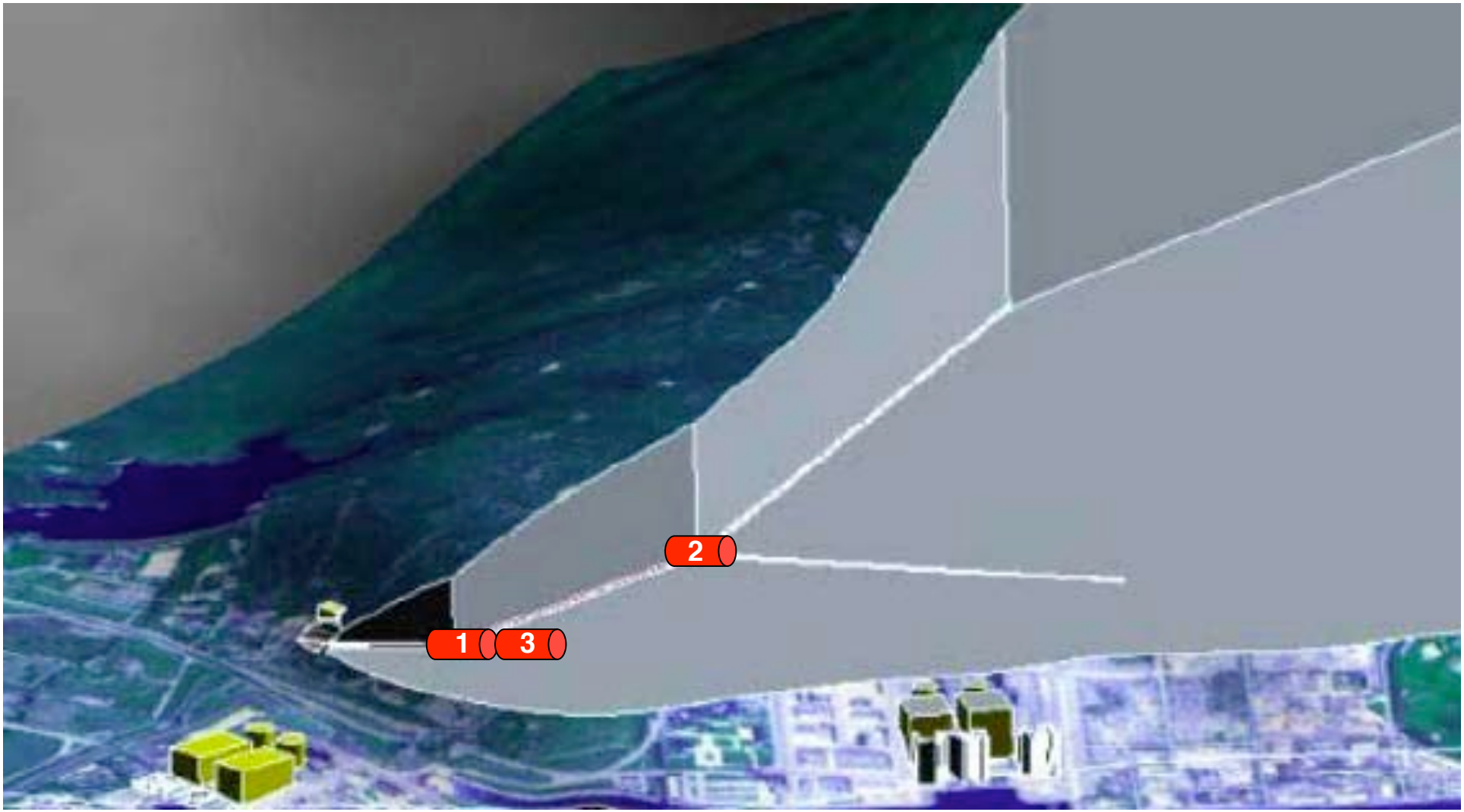
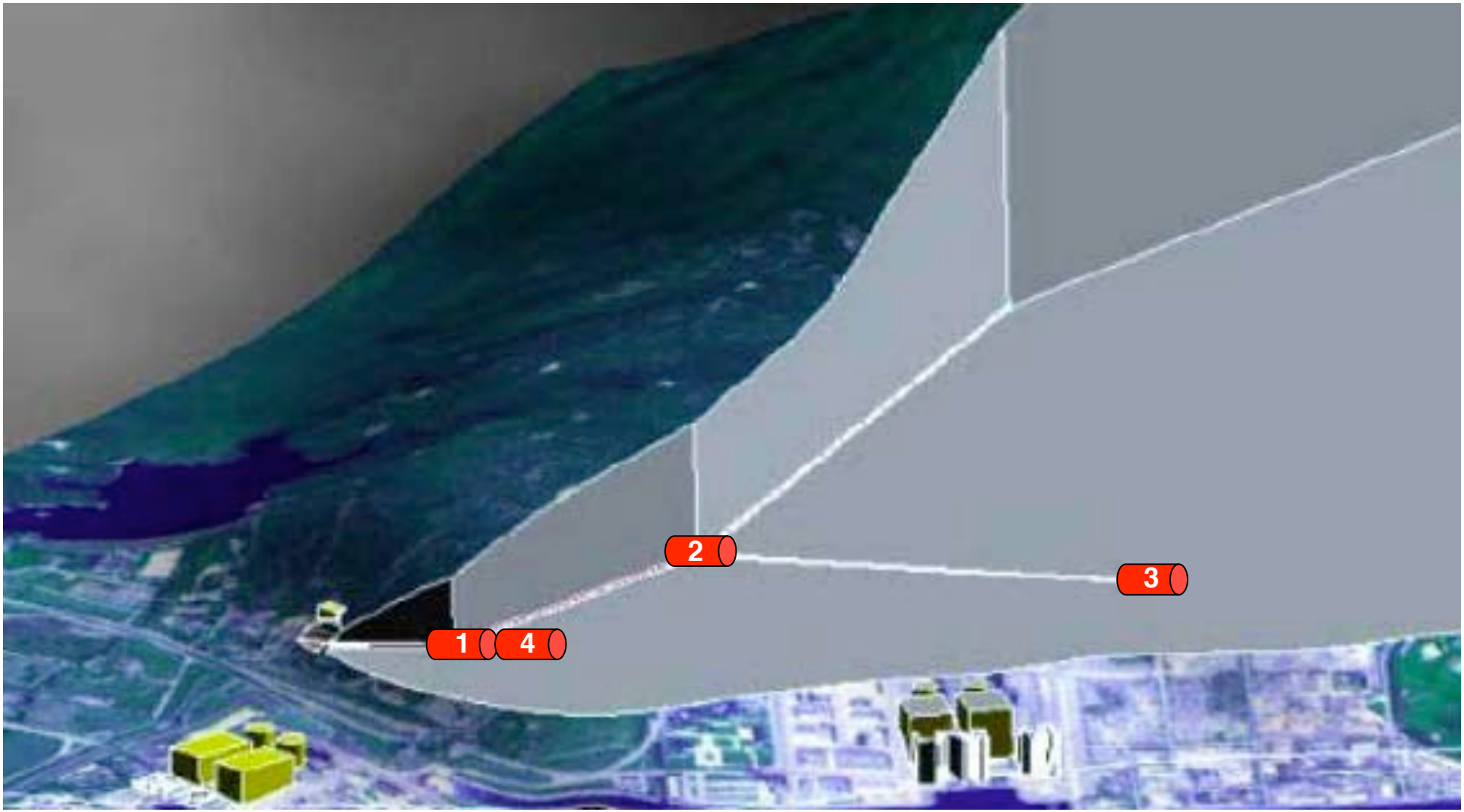
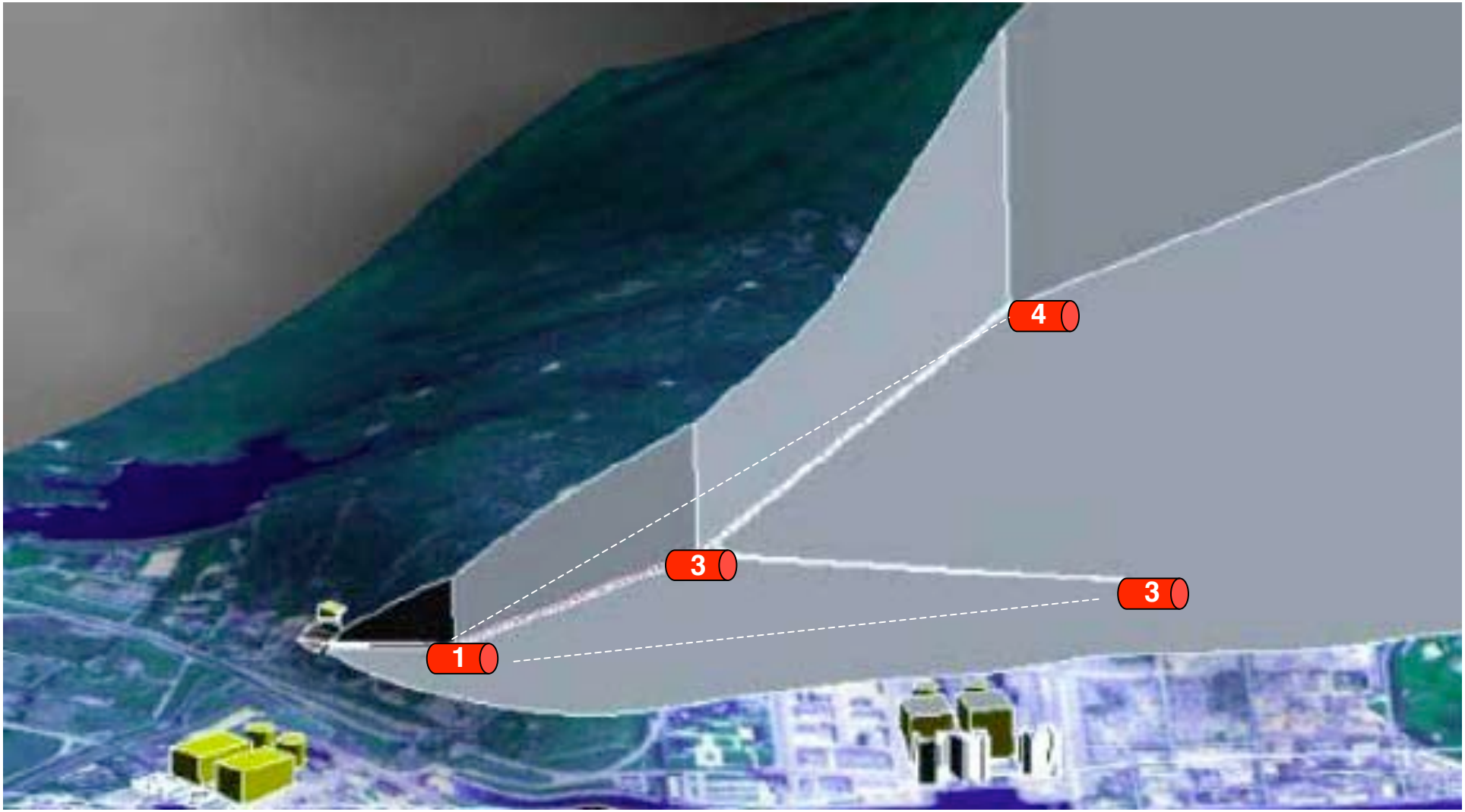


Illustration K. Chow

Deployment Strategy



Deployment Strategy



Staged Approach: Phase II Running

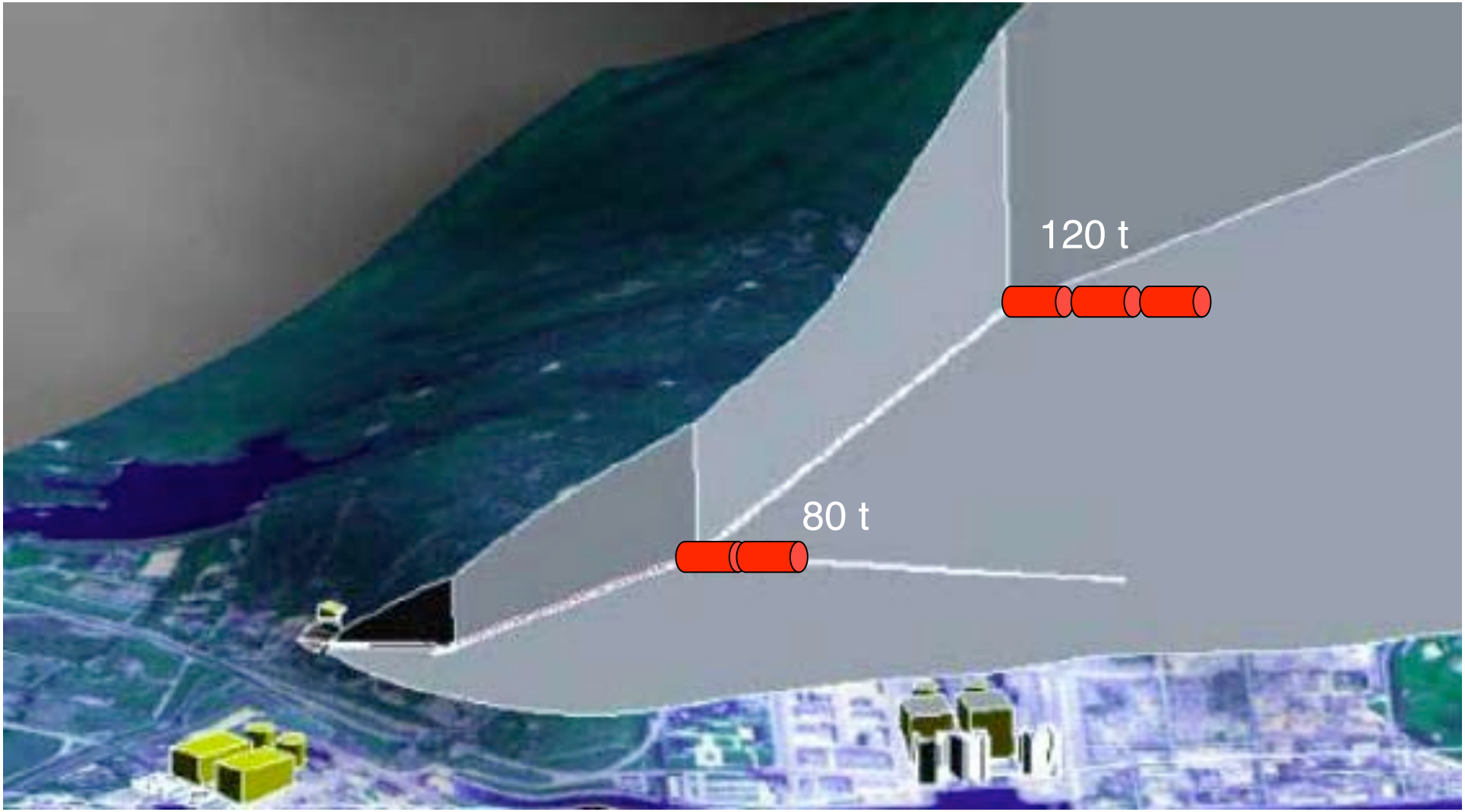


Illustration K. Chow

Staged Approach: Phase III Running

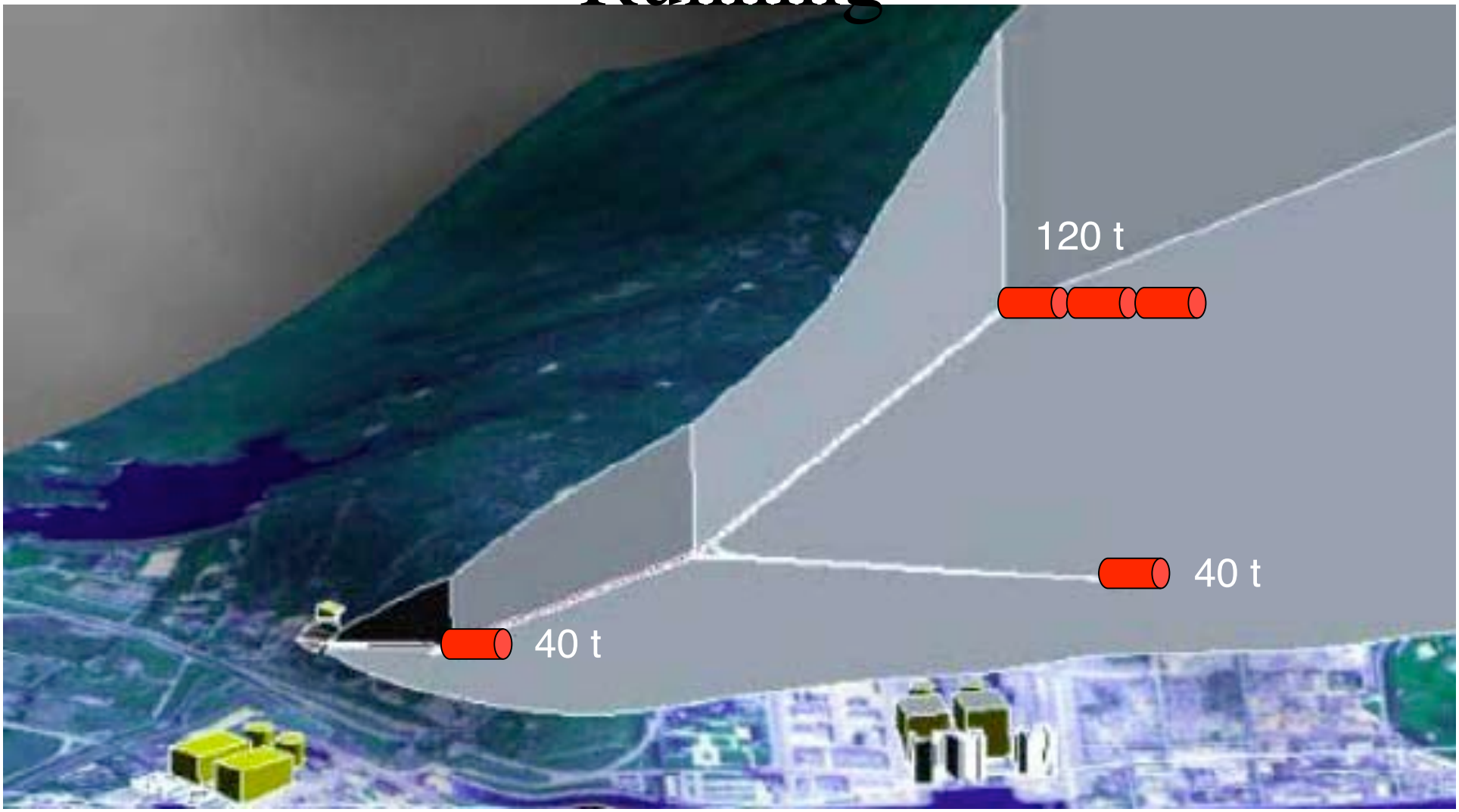


Illustration K. Chow

Another Possibility: Simultaneous near/mid/far

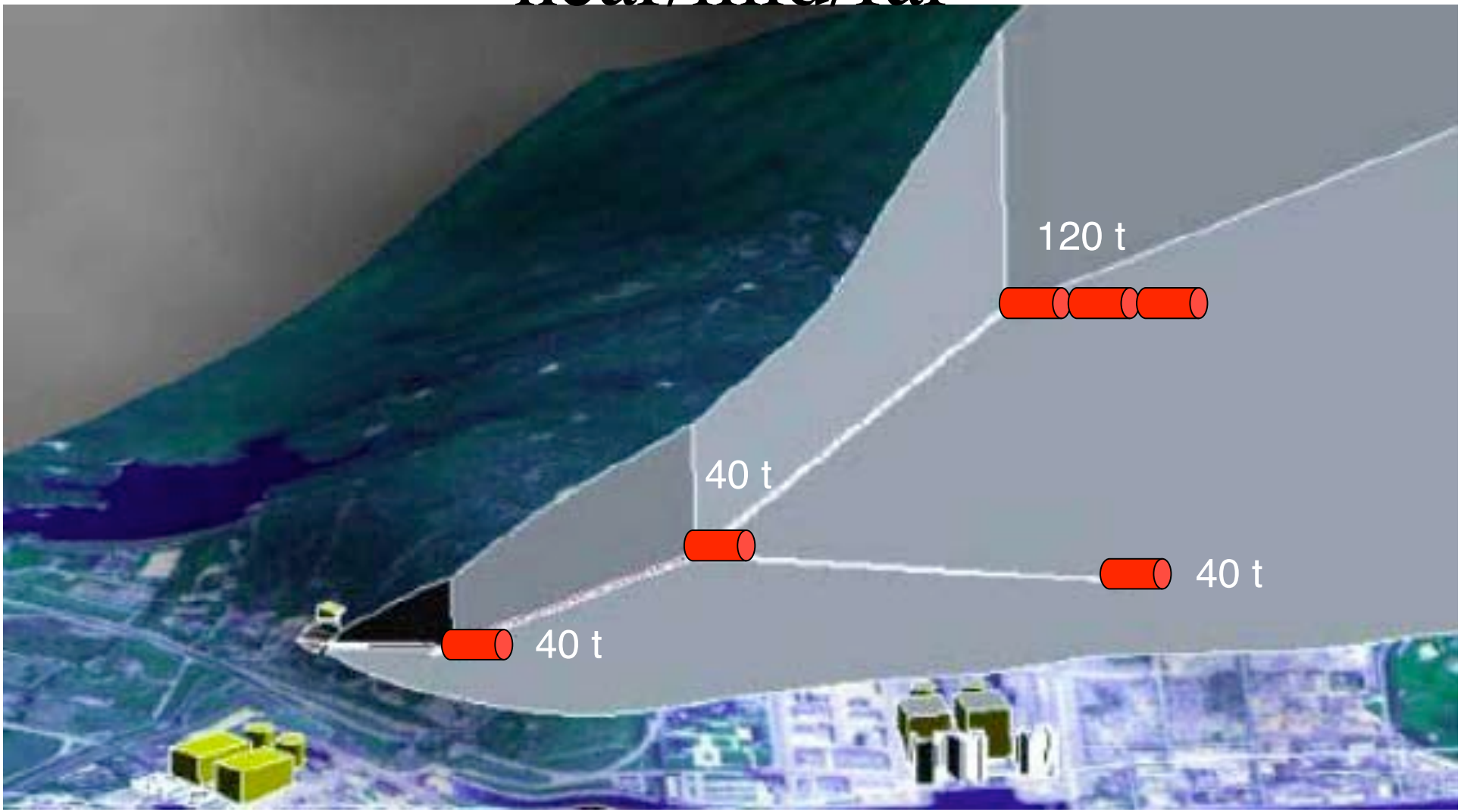


Illustration K. Chow

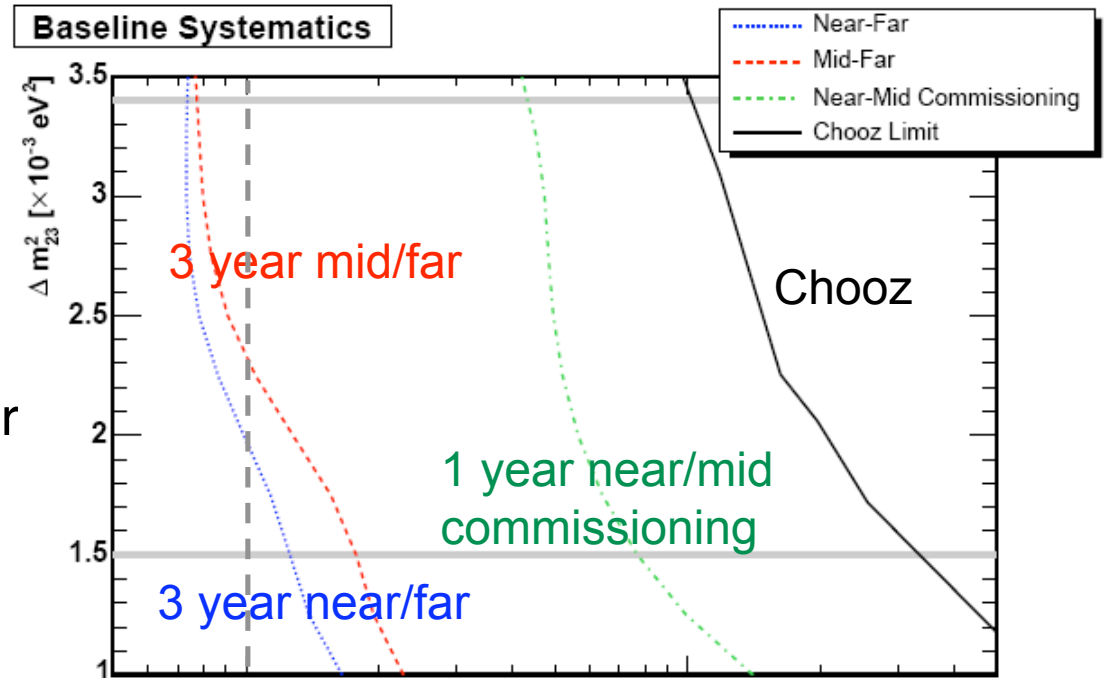
Sensitivity

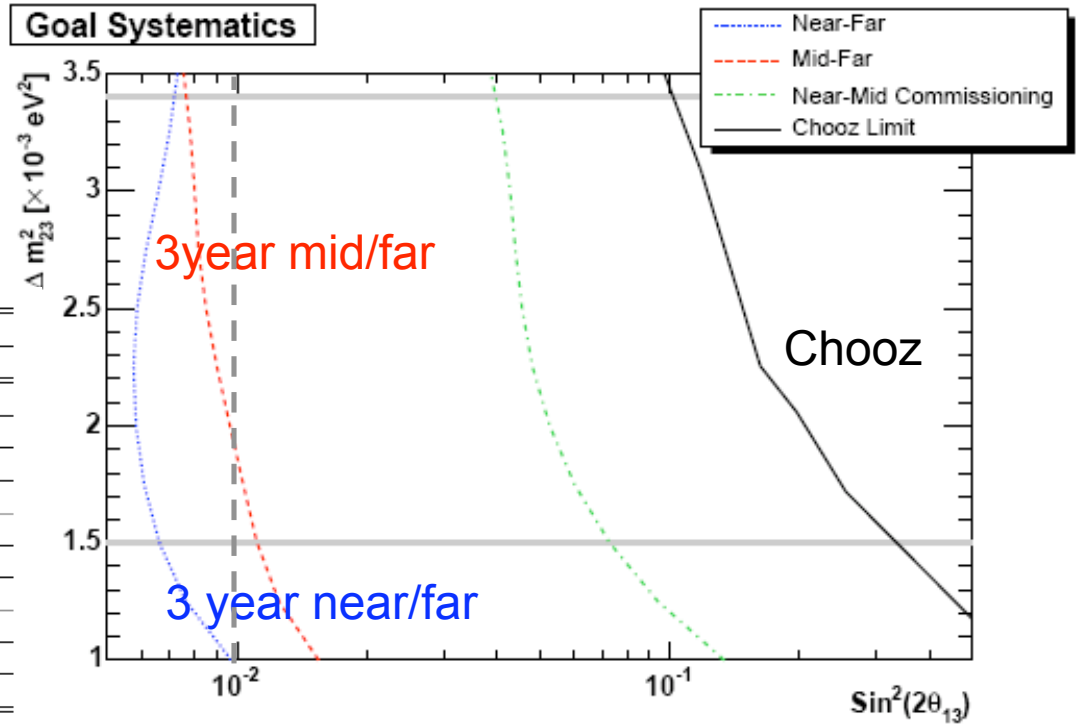
Scenario Total Tonnage (t)
near1/near2/mid/far

near/mid 40-0-40

mid/far 0-0-80-120

near/far 0-0-80-120





Source of error		CHOOZ	Daya Bay	
			Baseline	Goal
# protons	H/C ratio	0.8	0.2	0.1
	Mass	-	0.2	0.02
Detector	Energy cuts	0.8	0.2	0.05
Efficiency	Position cuts	0.32	0.0	0.0
	Time cuts	0.4	0.1	0.03
	H/Gd ratio	1.0	0.01	0.01
	n multiplicity	0.5	0.05	0.01
	Trigger	0	0.01	0.01
	Live time	0	< 0.01	< 0.01
Total detector-related uncertainty		1.7%	0.36%	0.12%

Timeline and Sensitivity of the Daya Bay Project

July 2007

Start of data taking at near and mid sites

2009

First result based on near and mid sites.

Start of data taking at far site.

2010

First result based on data from far site

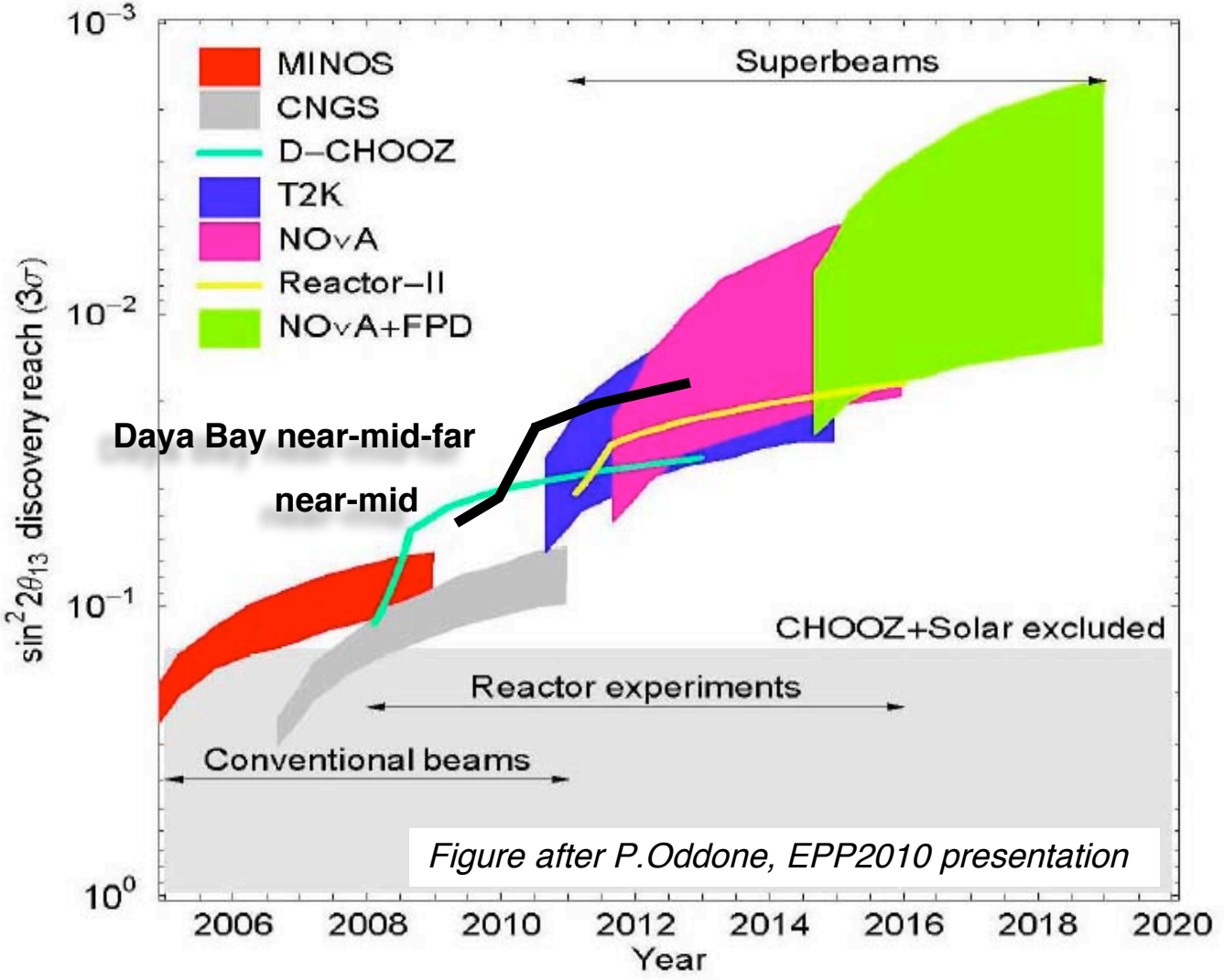


Figure after P.Oddone, EPP2010 presentation